

200 WATTS/KILOGRAM SOLAR ARRAY CONCEPTUAL APPROACH STUDY

PHASE II

ASSESSMENT REPORT

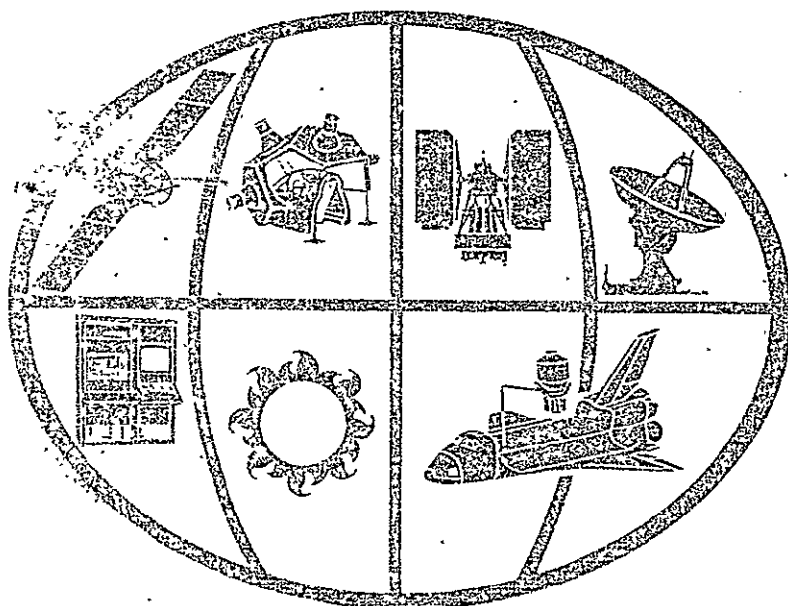
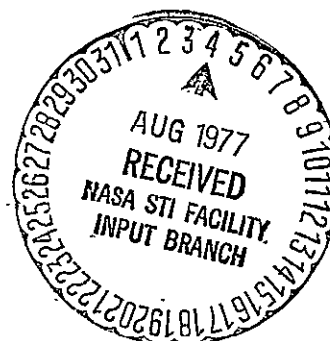
(NASA-CR-153938) THE 200 WATTS/KILOGRAM
SOLAR ARRAY CONCEPTUAL APPROACH STUDY.
PHASE 2: ASSESSMENT REPORT FOR
PROOF-OF-CONCEPT EXPERIMENTS AND HALLEY'S
COMET CONCENTRATOR ARRAY (General Electric

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200 WATTS/KILOGRAM SOLAR ARRAY
CONCEPTUAL APPROACH STUDY

PHASE II
ASSESSMENT REPORT

ASSESSMENT REPORT
FOR
~~PROOF-OF-CONCEPT~~ EXPERIMENTS
AND
HALLEY'S COMET CONCENTRATOR ARRAY

PERFORMED UNDER CONTRACT NO. 954393
FOR
THE JET PROPULSION LABORATORY
PASADENA, CALIFORNIA

GENERAL  ELECTRIC

SPACE DIVISION

Valley Forge Space Center

P. O. Box 8555 • Philadelphia, Penna. 19101



SPACE
DIVISION

200 W/Kg SOLAR ARRAY, PHASE II
HALLEY'S COMET CONCENTRATOR ARRAY



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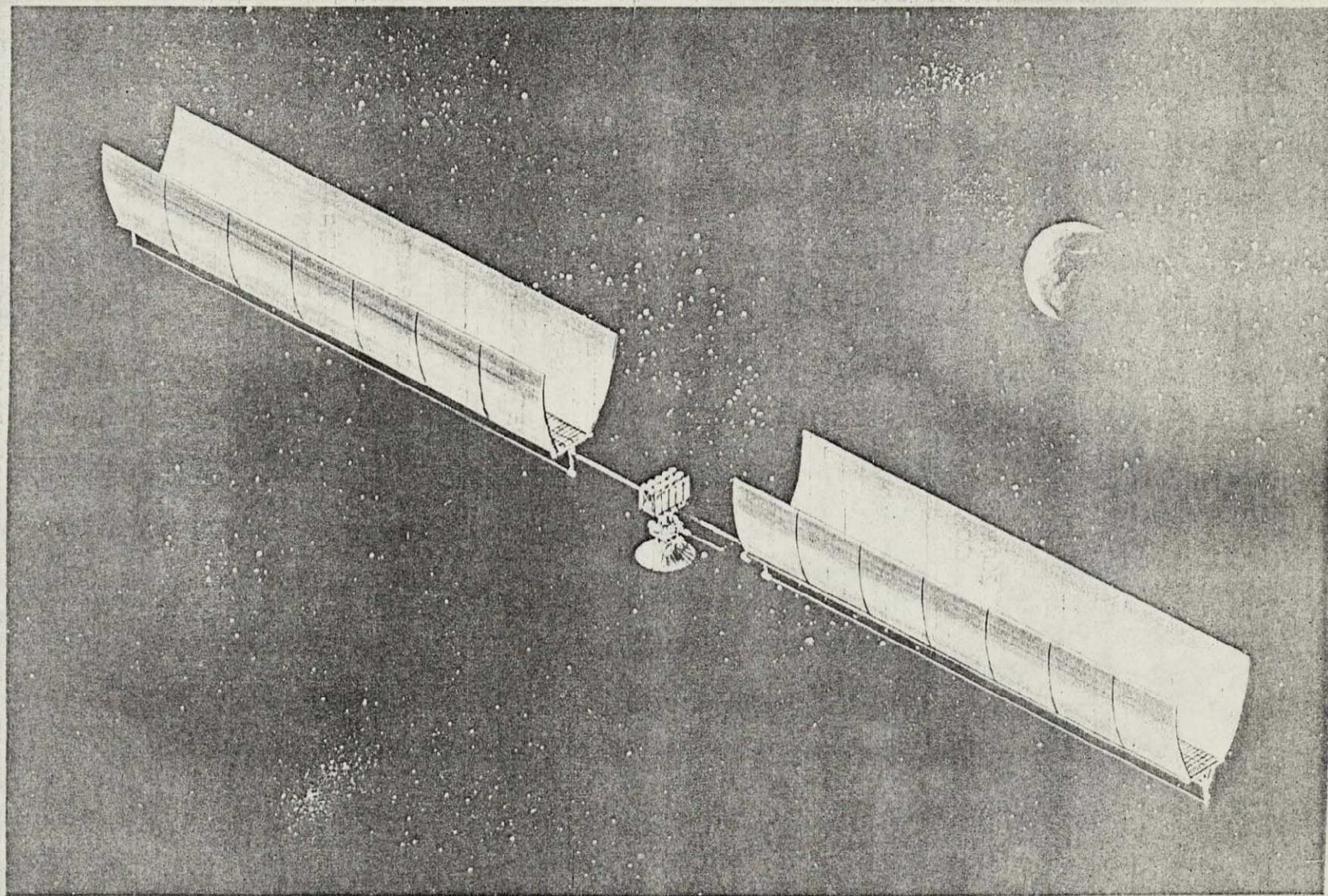


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EXECUTIVE SUMMARY

During the course of the 200 Watt per Kilogram Solar Array Program, several significant technological advances have been demonstrated that add to the overall readiness assessment being made for a lightweight solar array applicable to the Halley's Comet Mission. Although some system level concerns remain, much of the activities associated with the fabrication, handling, and testing of 2-mil solar cell modules on a flexible substrate have been successfully demonstrated. We have shown that 2-mil solar cells can be reliably handled, welded, and bonded to a Kapton substrate. Flexible Invar interconnects can be used to interconnect individual cells to form modules. These solar cell modules can be temperature cycled, wrapped around a 10-inch diameter drum, and vibrated to the Shuttle environment with no significant damage. We have developed a bonding technique to physically join adjacent modules that is stronger than the Kapton, itself. We have performed ultraviolet radiation tests on RTV - silicone as a cell cover material - with very encouraging results. In summary, we have successfully demonstrated the lightweight solar cell module technology readiness.

The activities undertaken to date on the Concentrator Solar Array for the Halley's Comet Mission have been conceptual in nature. Detailed analyses relating to areas such as flatness, natural frequency, temperature control, alignment, etc., have not been performed. However, projections have been made to quantify certain key parameters using the analytical results developed for the unconcentrated array. The results of these projections, coupled with an adequate conservatism, strongly indicate a technically feasible and practical design for the Halley's Comet Mission. However, additional effort is required to resolve the major open concerns. Detailed analysis and optimization studies should be performed in the areas of flatness, alignment, tension, concentrator efficiencies, stiffness, ground testing, and automated tooling. Materials testing should also be undertaken to better understand the radiation effects on the concentrator and cell cover materials. Additional testing of 2-mil cells at low temperature and low illumination will enable a more accurate prediction of solar array performance at far distances from the Sun.

The technology developed in the 200 Watt per Kilogram Solar Array Program will undoubtedly find its way into a wide variety of programs requiring large ultra lightweight solar arrays. It will benefit not only the Halley's Comet Mission, but other missions such as the Space Power Satellite. It is, therefore, incumbent upon us to keep this technology moving ahead.

Based on the work performed to date on this program, the solar array design proposed for the Halley's Comet Mission represents a technically feasible and practical approach. It incorporates the lightweight technology presently being successfully developed. An artist's rendering of the concentrator array design is shown as the Frontispiece of this report.

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SECTION 1

INTRODUCTION

Since January, 1977, General Electric Space Systems has been under contract with the Jet Propulsion Laboratory to:

1. Develop the technology required to fabricate and test ultra-thin solar cell modules utilizing a flexible substrate
2. Develop a conceptual solar array design to power the ion engines planned for use on the Halley's Comet Mission.

This report describes the activities undertaken and the results achieved to enable an overall assessment to be made of the technology readiness relating to the Halley's Comet mission solar array. The solar array design is based on the technology achievements made during the module development and test program, as is described in this report. The considerable amount of knowledge gained in the handling, welding, interconnecting, bonding, encapsulating, and testing of 2-mil thick solar cells on a flexible substrate has been applied to the concentrator solar array design for the Halley's Comet Mission. The feasibility of fabricating these ultra-thin modules has been demonstrated with a high degree of success.

SECTION 2
PRELIMINARY CONCLUSIONS

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The following preliminary conclusions are based on the solar array program activities undertaken to date. The detailed results are covered in this report.

1. Approximately 1457 2-mil solar cells have been processed through the manufacturing and test cycles at GE. Of these, 117 were initially rejected for various defects and not processed further; 330 were used for welding, encapsulation, or bonding tests; 120 were made into 4-cell modules for special evaluations; 270 were made into 9-cell modules for delivery to JPL; and 640 were made into 80-cell modules. At the start of the program, a reject or fall-out rate of about 44% was encountered. During the last two months, 640 cells were processed into 80-cell modules with a manufacturing reject rate of 9%. This successful reduction in rejects results from the knowledge gained in handling and assembling 2-mil cells together with the establishment of appropriate procedures.
2. Evaluations of several interconnect materials and configurations resulted in selecting a flexible design of silver-plated Invar.
3. Evaluations of several encapsulant cover materials resulted in selecting RTV silicone as both the encapsulant and the cell-to-substrate adhesive.
4. A welding schedule has been established that produces a strong repeatable cell-to-interconnect weld capable of surviving a temperature shock environment of -190°C to $+120^{\circ}\text{C}$, without damaging the cell electrical junction.
5. Temperature cycling tests at GE on test coupons produced no harmful effects.
6. Ultraviolet testing at GE (1000 hours at 1 equivalent UV suns) resulted in no loss in transmittance.
7. Ultraviolet testing at 10 EUVS at NASA/LeRC on RTV silicone and polyimide/siloxane showed RTV silicone to be on a par with an untried glass resin.
8. Pull testing on lapped-joined Kapton-to-Kapton using RTV silicone resulted in Kapton breaking before bond indicating a good bonding technique.
9. Wrapping five 80-cell modules bonded together around a 10-inch diameter drum 15 times resulted in no cell breakages.
10. Vibration testing of five 80-cell modules wrapped around a 10-inch diameter drum resulted in no cell breakage or module movement.
11. Electrical testing of over 1200 cells shows the repeatability of the 2-mil cell.

12. Solar cell modules consisting of 2-mil cells (2 cm x 2 cm), welded Invar interconnects, bonded to 1-mil Kapton substrates with RTV silicone, and covered with RTV silicone for radiation protection, can be readily assembled, tested, and handled. Such modules can survive temperature cycling of -190°C to $+120^{\circ}\text{C}$, can be wrapped around a 10-inch diameter drum with no cell breakages, can be vibrated to the shuttle launch environment with no cell breakages, and can survive a 1000 hour UV exposure with only a 11% power loss, maximum.
13. Creep Testing of a module and lap joint resulted in zero elongation.
14. The solar cell module fabrication and test program proves that 2-mil cells mounted on a flexible substrate can meet the requirements of the Halley's Comet Mission Solar Array Design.

A representative sample of the product produced in this phase of work is shown in Figure 2-1, along with a diagramic sketch of a typical cross-section through a solar cell assembly.

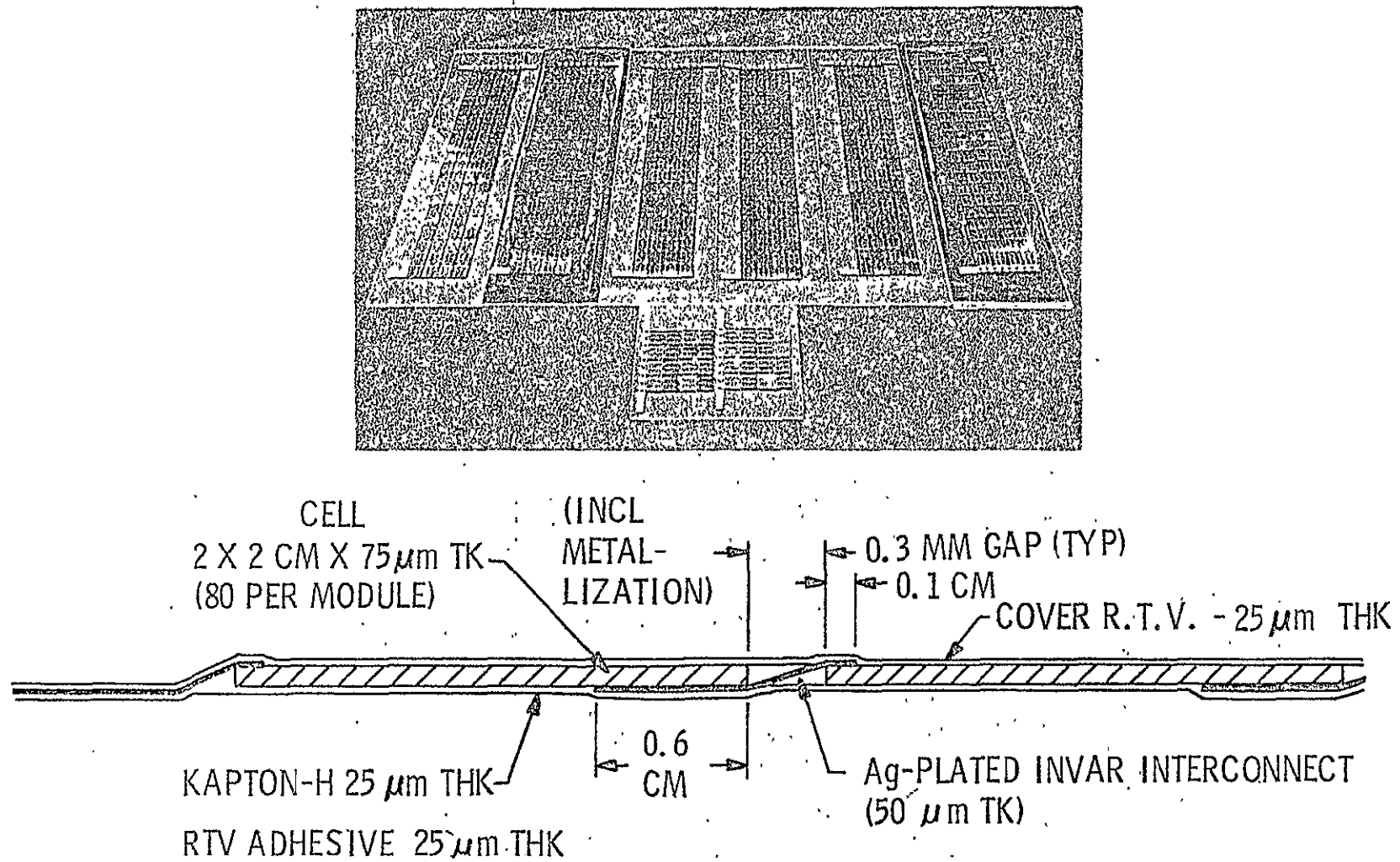


Figure 2-1. 80 Cell Module & 16 Cell Test Coupons

SECTION 3

TECHNOLOGY ASSESSMENT

3.1 INTRODUCTION AND SUMMARY

Beginning in mid-January 1977 and ending in June 1977, an experimental program was implemented to assess the soundness of the design concepts identified during the preceding Phase I conceptual design study. Whereas Phase I was a generic study of design techniques, manufacturing methods and materials that together could lead to an ultralight solar array, the Phase II work was directed specifically in a manner to meet the system requirements of the Halley's Comet rendezvous. The proof-of-concept experiments that were conducted were designed to test and validate the ultra-lightweight design against environmental conditions imposed by a Shuttle launch of the Halley's Comet rendezvous spacecraft into an interplanetary orbit that could be as close to the sun as 0.6 AU and as far away as 4.5 AU. This work was unique in that no prior experimental work had been done to directly support the 200W/Kg solar array conceptual design. Working drawings had to be created from engineering sketches, materials had to be ordered, and manufacturing tools had to be designed and fabricated. Test plans were created to: (1) simulate Shuttle launch vibration; (2) simulate UV exposure at earth orbit; (3) test materials over temperature extremes anticipated with a concentrator solar array; and (4) prove that ultra-thin solar cell arrays may be rolled-up on a circular storage drum without deleterious results. It may be noted that no prior experience existed for either manufacturing or testing of solar modules involving 2-mil thick solar cells.

While not all the test results are in at this writing (a 1000-hour UV exposure test is still in process); it may be concluded on the basis of the work completed that the basic soundness of an ultra-thin solar cell array with specific powers (watts per unit mass) at the module level of 370 watts is a proven fact. Future work should be directed toward improvements in cell electrical efficiency and optimization of array design parameters so that this extremely high value of specific power will not be diluted unduly at the system level.

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3.2 PROOF-OF-CONCEPT TEST PROGRAM

The objective during this accelerated test program was to demonstrate that the advent of the 2-mil silicon solar cell could be capitalized on to produce high quality, ultra-lightweight solar arrays following the design principles outlined in the preceding phase of work. The scope of this activity included product design, material evaluation, production of test coupons and solar modules, environmental tests, demonstration of roll-up stowage and performance evaluation. This work had to be accomplished in five months because of the dictates of the Halley's Comet rendezvous program evaluation schedule. A test program schedule was developed whereby key delivery dates could be met and which accounted for all the required elements of work. The overall program schedule, as shown in Figure 3-1, was divided into two principal parts - the production and test of test coupons, and the production and test of 80-cell modules. Three important processes had to be addressed at the beginning; viz, (1) weld bonding of interconnects to cells; (2) thermal bonding of welded cell assemblies to the flexible substrate; and (3) final encapsulation of the cell/substrate assembly in a protective covering. Although the issue of weld bonding vs. solder bonding had been resolved in favor of weld bonding during the Phase I study, a small side experiment (not identified in the above bubble charts) for solder bonding was conducted as a hedge on weld bonding. Solder bonding offers no advantages in the assembly of interconnects and solder cells, by our experience. Solder bonding requires excessive clean-up both before and after soldering and more careful handling of the product in the manufacturing process. When consideration is given to the temperature limit and the additional weight imposed by solder bonding, there appears to be no merit to solder bonding in an ultra-lightweight solar array. A summary of the experience with weld bonding is given in Table 3-1 and the overall conclusions of the proof-of-concept program is shown in Table 3-2.

3.2.1 MATERIAL EVALUATION

Three material items were identified for laboratory test and evaluation; viz, silver-plated interconnects, substrate cement and cell encapsulation. The Phase I study identified silver-plated molybdenum as the optimum interconnect and FEP-Teflon as the substrate cement and encapsulant. During the course of laying out the program plan, a decision was made to incorporate alternate materials in the test plan.

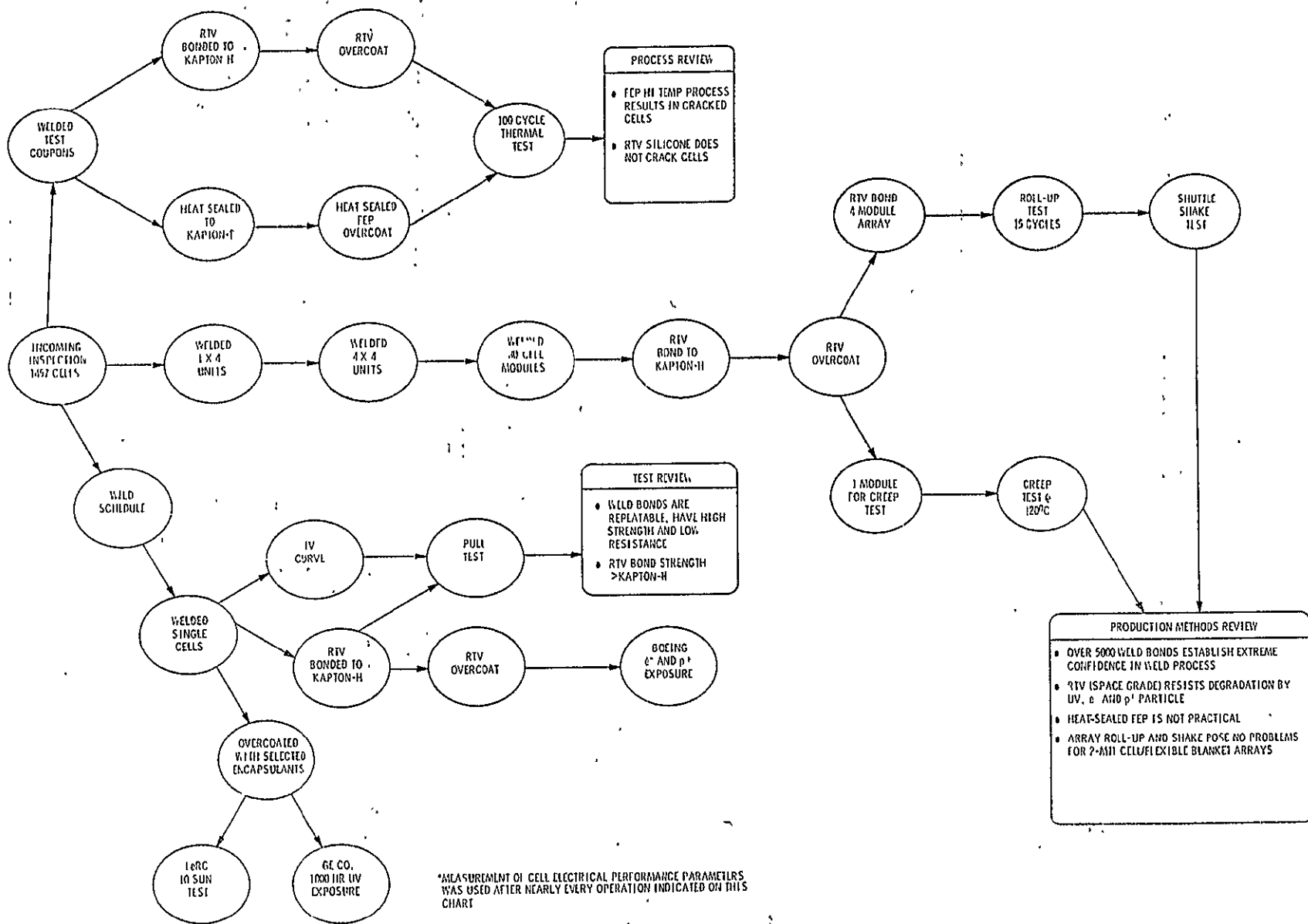


Figure 3-1. Proof-of-Concept Experiment 200 Watt/Kilogram Solar Array Program

Table 3-1. 200 W/Kg Solar Array Conceptual Design Study, Phase II

Cell Processing Summary

Item	Quantity	Total Cells	Weld Bond
Welded Single Cells	42	42	84
Welded 1 x 4 Cell Unit	185	740	1480
Welded 2 x 2 Cell Unit	30	120	480
Welded 2 x 4 Cell Unit	5	40	80
Welded 3 x 3 Cell Unit	30	270	1080
Welded 4 x 4 Cell Unit	49		1568
Welded 80 Cell Modules	8		320
Cell Rejects, Broken in Process, etc.	<u>245</u>	<u>245</u>	
		1457	5092

Yield at Various Stages of Module Manufacture -- June 1977:

Incoming Inspection	0.92
1 x 4 Unit, After Welding	0.96
4 x 4 Unit, After Welding	0.98
80 Cell Module, After Welding	0.99
80 Cell Module, After Cementing	0.99+
80 Cell Module, After Encapsulation	0.99+

Table 3-2. Proof-of-Concept Experiments Summary

Objectives Were Successfully Met

- Interconnect design survived thermal fatigue test
- Weld bonding shows high bond integrity under thermal and vibration stress
- RTV silicone shows no degradation at 1 EUV and does not cause cell fracture
- RTV-silicone bond is stronger than the Kapton substrate at 15,000 psi
- Four 80-cell modules survived 15 cycles of wrap and unwrap on 10" dia drum
- The stowed array withstood shuttle launch environment

Conclusion

- Proof-of-concept for a 2-mil cell, flexible array, roll-up storage has been accomplished

3.2.1.1 Silver-Plated Interconnects

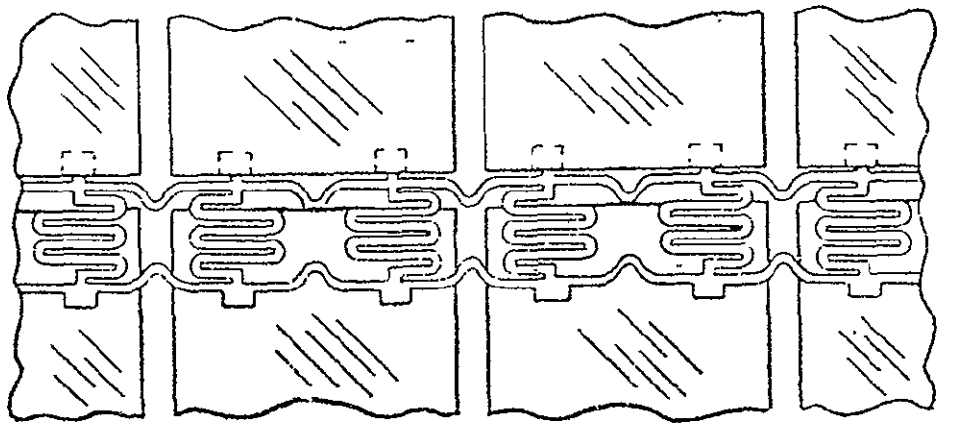
Three materials, moly, Invar and Elinvar, were tested during the course of this phase of work. Two interconnect designs, Figures 3-2 and 3-3, were used as a flexible and stiff interconnect respectively. The results of weld strength and electrical measurements were used as an evaluation criteria, called weldability, to rank the materials. Thermal shock and thermal cycle test results were used to rank the materials and design configurations. These findings are summarized in Table 3-3. The original criteria for selecting moly as the best interconnect material was based on (1) its high strenght-to-weight ratio (specific stiffness), and (2) its coefficient of thermal expansion which matches very closely that of silicon. A pragmatic problem impeded the full evaluation of moly, however. It was very tedious at best and very erratic at worst to get a good, tenacious silverplate on moly. A nominal 0.5-mil plate of silver is essential to obtain sound, repeatable weld bonds. Further work on silver-plating of moly will be required before this non-magnetic material may be fairly evaluated as an interconnect material. There appears to be enough weld strength data to state a preference for Ivar over Elinvar⁽¹⁾. Both of the high nickel content metals take a silver-plating equally well. The major problem which surfaced during the thermal cycle tests is the propensity of the stiff interconnect to break cells. The obvious advantage of the so-called stiff design is its rather large weight advantage. A compromise interconnect design incorporating some of the features of both is the next logical step.

3.2.1.2 Substrate Cement

Three materials were evaluated as cements for bonding the cell/interconnect assembly to the Kapton substrate, see Table 3-4; viz, a flexible epoxy known as SMRD 745, RTV silicone, and FEP-Teflon. Of the three, REP-Teflon was pre-processed with the Kapton substrate and purchased as Kapton-F. The epoxy and silicone are both two-part cements that were mixed and applied at the time of cementing. Heat sealing of FEP-Teflon to the cell backs at 250°C was accomplished with sufficient adhesion to crack cells when the bonded assembly was cycled in temperature from -190°C to 120°C. The same results were encountered with the flexible epoxy. Excellent results were experienced, however, with RTV-silicone which was cured at

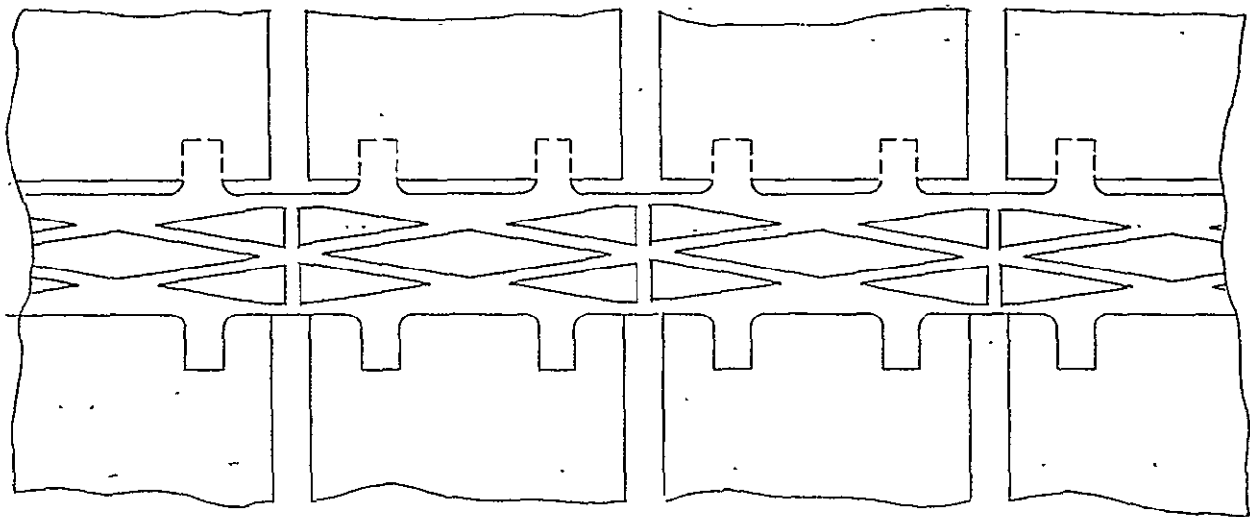
(1) Proprietary Alloy of Hamilton Technology

65°C to accelerate the cure cycle. Moreover, when the RTV silicone was used as the bond for a lap joint of Kapton against Kapton, the bond proved to be stronger than the 1-mil Kapton-H material itself.



1 MIL INVAR
0.5 MIL Ag
BOTH SIDES

Figure 3-2. Flexible Design



1 MIL INVAR
0.5 MIL Ag,
BOTH SIDES

Figure 3-3. Stiff Interconnect Design

Table 3-3. Interconnect Evaluation

Interconnect Design	Moly	Invar	Elinvar	Comparative Mass
Stiff Weldability Thermal Cycle	Poor Poor	Excellent Poor	Good Poor	1
Flexible Weldability Thermal Cycle	Good Poor	Excellent Good	Good Good	4
Material Specifications	1-mil (99.5% pure) Moly 0.5 Ag, both sides	1-mil Invar 63.2% Fe 36% Ni 0.5-mil Ag, both sides	1-mil Elinvar 48% Fe 43% Ni 5% Cr 2-3/4% Ti 0.5-mil Ag, both sides	

Flexible Invar Interconnect is Best
Need Further Work in Ag-plating of Moly
Need Weight Reduction on Flexible Design

Table 3-4. Substrate Cement Evaluation

Cement	Form	Method of Application	Applicable Temperature	Survivability in Thermal Cycle (-190°C to 120°C)	Bond Strength
FEP-Teflon	Laminated to Kapton	Heat sealed under pressure	250°C	Poor	Fair
Flexible Epoxy SMRD-745	2-part formula	Spatula or brush	140°C	Poor	Good
RTV-Silicone	2-part formula	Spatula or brush	Room Temperature to 65°C	Excellent	Excellent

High Temperature Processes Crack Cells
RTV Silicone is Superior

3.2.1.2 Encapsulant

Following the conclusions of the earlier conceptual design study, a continuous protective cover was desired as an encapsulant for both solar cells and interconnects. Eleven material formulations of polymeric materials were evaluated for comparative merit. In addition to FEP-Teflon, RTV-Silicone and several formulations of a copolymer of polyimide and silicone were tested. Again the processing temperature was the determining factor in maintaining cell/interconnect integrity. The RTV silicone, with its low temperature processing feature, is a clear winner among those materials processed as encapsulants. The one sun 1000-hour UV exposure test showed that the RTV-Silicone and the co-polymer BE124H ⁽¹⁾ were unaffected by UV. In a 10 sun test at NASA's Lewis Research Center, after 728 hours exposure, the RTV-silicone proved to be superior to the same co-polymer.

RTV-silicone was selected as the best of the evaluated materials for three reasons; low temperature processing, UV resistance, and ease of processing.

3.2.2 DESIGN EVALUATION

The status of the ultra-lightweight, flexible blanket concept may be summarized as follows.

Ultra-thin silicon solar cells may be rolled-up on a 10-inch diameter drum without catastrophic failure. Wrap-around contacts are not required with 2-mil thick solar cells. Planar, flexible interconnects made from silver-plated Invar have passed every test given them. The low-temperature processed adhesive and encapsulant does not lead to thermally induced stress great enough to break cells or bonds. The RTV silicone class of adhesives and encapsulants are superior to any other material tested during the course of this program. The low temperature processed co-polymer of polyimide and silicone shows promise and should be further evaluated. The weld bonding process has been proven successful and is to be preferred over solder bonding for the reasons enumerated above. The fully encapsulated cell/interconnect assembly cemented to Kapton-H proves to be a very rugged assembly, resistant to temperature cycling, vibration cycling, roll-up on curved surfaces and creep under load. A summary of properties for the 80-cell module is given in Table 3-5.

(1) Bergston & Associates - Schenectady, N.Y.

Table 3-5. 80-Cell Module, Summation of Properties

<u>Mass Breakdown</u>	
2-mil Cells	78 mg
#580 Interconnect	31.3 mg/cell
Kapton-H	14.5 mg/mil-cell
RTV-655	10.9 mg/mil-cell
For the 80-Cell Module:	
80, 2-mil Cells	6.24 g
80, #580 Interconnects	2.50
1-mil Kapton-H (8.2 cm x 41 cm)	0.85
3-1/2-mil RTV-655	3.05
Total Mass Per Cell	158 mg
Maximum Power at 28°C:	
P _m , 80-Cell Module	4.72 Watts
P _m , per Cell	59 mW
Specific Power:	373W/Kg

3.2.3 MANUFACTURING PROCESS DEVELOPMENT

3.2.3.1 Weld Bonding

A weld bonding schedule has been developed that is repeatable and reliable in the quality of bonds produced. Hot welds (cell junction is destroyed) are minimal as long as the cell has sufficient thickness (0.3-mil to 0.5-mil) of metallization. Cold welds may be readily detected and corrected by a second current pulse in most cases. Overall yield is better than 90%.

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3.2.3.2 Cement Bonding

Strong tenacious bonds may be made with space qualified RTV-silicone at low to moderate curing temperatures. The elastomeric properties of silicone offer a resilient bond that is helpful in protecting the cell/interconnect from mechanical damage. Bond strengths for RTV-silicone exceed that of the Kapton-H substrate.

3.2.3.3 Cover Material Bonding

A manufacturing process has been developed which permits a uniform, thin RTV silicone coating to be applied and cured with a minimum of equipment and almost zero production loss. A cure period of 1-hour at 65°C is sufficient to polymerize this material.

3.3 LABORATORY TEST RESULTS

3.3.1 THERMAL CYCLE TESTS

A total of 12 thermal cycles were run on individual cells, test coupons, and 16 cell sub-modules. In all cases the items under test were clamped at one or more points to the heat sink/source via the metal interconnect to get good thermal contact. One or more thermocouples were soldered to the interconnects to measure cell temperature. The entire assembly was wrapped in a metal-foil shroud to control thermal emittance. A summary of these tests is listed in Table 3-6. The second objective listed in this table has not been met because the thermal/UV test cycle (1200 hours) is still in process at this writing.

Table 3-6. Temperature Cycling

<u>Objectives</u>
• Stress total cell, interconnect, cement and substrate over extreme temperature range (-190°C to 120°C) • Repeat after UV exposure
<u>Procedure</u>
• Measure IV characteristic before and after test • Attach test coupon to heat sink/source • Cycle 100 times at ~ 5°C/min • Inspect for cracked cells, open interconnects, etc.
<u>Conclusions</u>
• FEP-Teflon, heat sealed at 250°C, results in cracked cells • RTV silicone, cured at 65°C, does <u>not</u> result in cracked cells • There are no signs of fatigue in the Invar interconnect • The non-compliant interconnect is not fully evaluated at this time

3.3.2 UV EXPOSURE TEST

One 1000-hour UV exposure test is complete and a second is in process at this time. The first test was conducted on single cells overcoated with a selection of cover materials; viz, FEP-Teflon, RTV-silicone, polyimide and several formulations of a polyimide/silicone co-polymer. Each cell was attached to a heat source through a metallic interconnect so that each test item could be maintained at a steady 120°C throughout the duration of the tests. Periodically, readings of I_{sc} and V_{oc} were recorded, along with a measurement of surface reflectance at 400 nm. The latter reading was made via an integrating sphere incorporated in the vacuum test stand. Both UV exposure and 20 Kev electron fluence were obtained concurrently. The former radiation, originating with a 2.5 Kw high-pressure mercury-Xenon arc, was adjusted to provide an illuminance at the samples under test of one equivalent UV sun (EUVS). The total low energy electron dosage over the 1000-hour test was 10^7 rads. This test is summarized in Table 3-7. The solar and thermal band optical constants for RTV silicone, before and after this test are shown in Table 3-8. These results compare very favorably to FEP-Teflon measured earlier.

Table 3-7. UV Exposure Test

<u>Objective</u>
• Comparative evaluation of candidate cover materials under simulated UV exposure and low energy electron dosage
<u>Procedure, GE Co.</u>
• Expose 11 samples of selected polymers and co-polymers at 120°C to H _g -Xe lamp at 1 equivalent UV sun (EUVS) and 20 Kev fluence
• Monitor IV characteristics and surface reflectance at 400 nm
<u>Conclusions</u>
• The optical properties of the polyimide, 20% polyimide/80% siloxane and RTV silicone coatings were unaffected through this exposure to 1 EUVS and 10^7 rads
• LeRC tests at 10 EUVS for 728-hours showed a 17% change in I_{sc} for RTV silicone, comparable to the best glass resin

Table 3-8. Absorptance and Emittance of RTV Coated Cells Cemented to Kapton-H

<u>Top Surface Measurements</u>		
Materials:		
3-mil RTV-655 over Solarex 2-mil Silicon Solar cells		
1/2-mil RTV-655 as adhesive between cells and substrate		
1-mil Kapton-H substrate		
Measurements:		
	Before IV Exposure	After 1000 Hours UV Exposure (1 Sun)
<u>Top Surface</u>		
Reflectance (0.1 μm to 10 μm)	0.16	0.13
Absorptance (2.5 μm to 28.5 μm)	0.05	0.13
(0.1 μm to 10 μm)	0.84	0.87
Emittance, normal (100°F)	0.94	0.87
<u>Back Surface</u>		
Reflectance (2.5 μm to 28.5 μm)	0.18	--
Emittance, normal (100°F)	0.82	--

3.3.3 ROLL-UP TEST

A mockup of a 10-inch diameter storage drum was used as a test vehicle for a simulated four-module solar array. Four 80-cell modules were bonded together and equipped with flat conductor cable buses on both sides of the assembly. The 80-cell modules represented a full-scale module in the direction of wrap, but only a small fraction of the design width of the module. The total length of the assembly was sufficient to provide 2-1/2 wraps around the 10-inch drum. The assembly was wrapped under the load per unit length (29.2 N/m) prescribed in the array design. A total of 15 cycles of wrap and unwrap of this assembly did not result in any broken cells or interconnect bonds. The RTV silicone cement and overcoat showed no signs of delamination. Subsequent measurement of the IV characteristic on each module showed a 3% to 9% loss in maximum power and fill factor losses ranging up to 11%. In no case was the fill factor less than 70%. This test is summarized in Table 3-9.

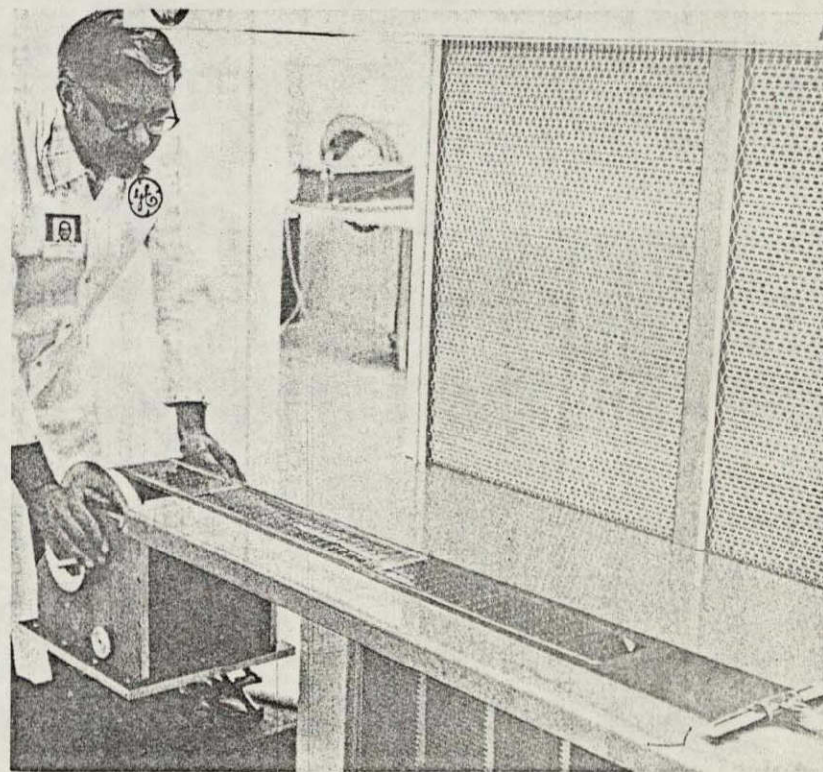
Table 3-9. Roll-up Test

ROLL-UP TEST

- PURPOSE
 - DEMONSTRATE FEASIBILITY OF BLANKET ROLL-UP
- TEST RESULTS
 - NO CRACKED CELLS AFTER 15 ROLL-UPS
 - MODULE P_{mp} LOSSES RANGED FROM 3% TO 9%
 - MODULE FILL FACTORS ≥ 0.70

VERIFIED FLEXIBLE BLANKET ROLL-UP CONCEPT

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3.3.4 VIBRATION TEST

Subsequent to the roll-up test, the wrapped-up assembly of four modules was placed on a shake machine where a simulation of the Shuttle launch environment was imposed on it. The test unit was shaken in two orthogonal axes (the third axis being a redundant transverse axis). No cells were broken. No interconnects were damaged. A minimal loss of P_{max} and fill factor were noted. There was no translational movement of the test assembly along the axis of the drum. This test is summarized in Table 3-10.

Table 3-10. Vibration Test

<u>Objectives</u>	
•	Expose array model to simulated shuttle launch vibration environment
•	Test for vibration induced array malfunction
<u>Procedure</u>	
•	Wrap four-module array on 10-inch diameter drum under the prescribed tension
•	Vibrate the assembly in each of 3 orthogonal axes:
	4 to 5 Hz 1 inch DA
	5 to 25 Hz 1.4 g (0-peak)
	25 to 50 Hz 0.036 inch DA
	50 to 1000 Hz 5 g (0-peak)
•	Visually inspect and compare IV characteristics before and after test
<u>Observations</u>	
•	No cracked cells
•	$\Delta P_{mp} < 2\%$, $\Delta FF < 3\%$
<u>Conclusions</u>	
•	A flexible blanket rolled-up under tension will suffer <u>no</u> loss in a shuttle launch vibration environment.

3.3.5 CREEP TEST

As a test of module and lap joint elongation under load and at an elevated temperature, a test was conducted whereby an 80-cell module and associated substrate lap joint were suspended from a test fixture in a thermal chamber. The unit under test was loaded at the level (29.2 N/m) used in the roll-up test. After 24-hours at 120°C no measurable creep was observed.

3.3.6 ELECTRICAL TEST

Repeated use of Spectrolab's Large Area Pulsed Solar Simulator (LAPSS) was made during the course of manufacture and test of cells, test coupons, and modules. A standard cell, supplied by JPL, was used as a zero air mass reference. An IV curve was obtained at each test enabling I_{sc} , V_{oc} , I_{mp} , V_{mp} and P_{mp} to be readily observed. It may be noted, however, that a visual inspection must accompany each electrical test. There were times, for instance, when a normal IV curve could be obtained on a test article that had one or more broken cells. A summary of the conclusions of this test is given in Table 3-11.

Table 3-11. Electrical Testing

<u>Purpose</u>
In-process test of product health
<u>Implementation</u>
Spectrolab's Large Area Pulsed Solar Simulator (LAPSS)
<u>Procedure</u>
IV curve is taken after each weld bonding stage as well as cement bonding and encapsulation
<u>Conclusion</u>
• Monitoring of I at 470 mV is sufficient at incoming inspection • LAPSS provides all necessary data I_{sc}, V_{oc}, I_{mp}, and V_{mp} to quickly diagnose state of health

SECTION 4

CONCEPTUAL SOLAR ARRAY DESIGN FOR HALLEY'S COMET MISSION

This section describes the conceptual design for a concentrator solar array utilizing the 2-mil solar cell module development technology described in Section 3. Section 5 briefly summarizes the array performance if a 6-mil solar cell of 13.5% efficiency were used.

4.1 SOLAR ARRAY REQUIREMENTS

The solar array requirements to meet the Halley's Comet Mission objectives are listed in Table 4-1.

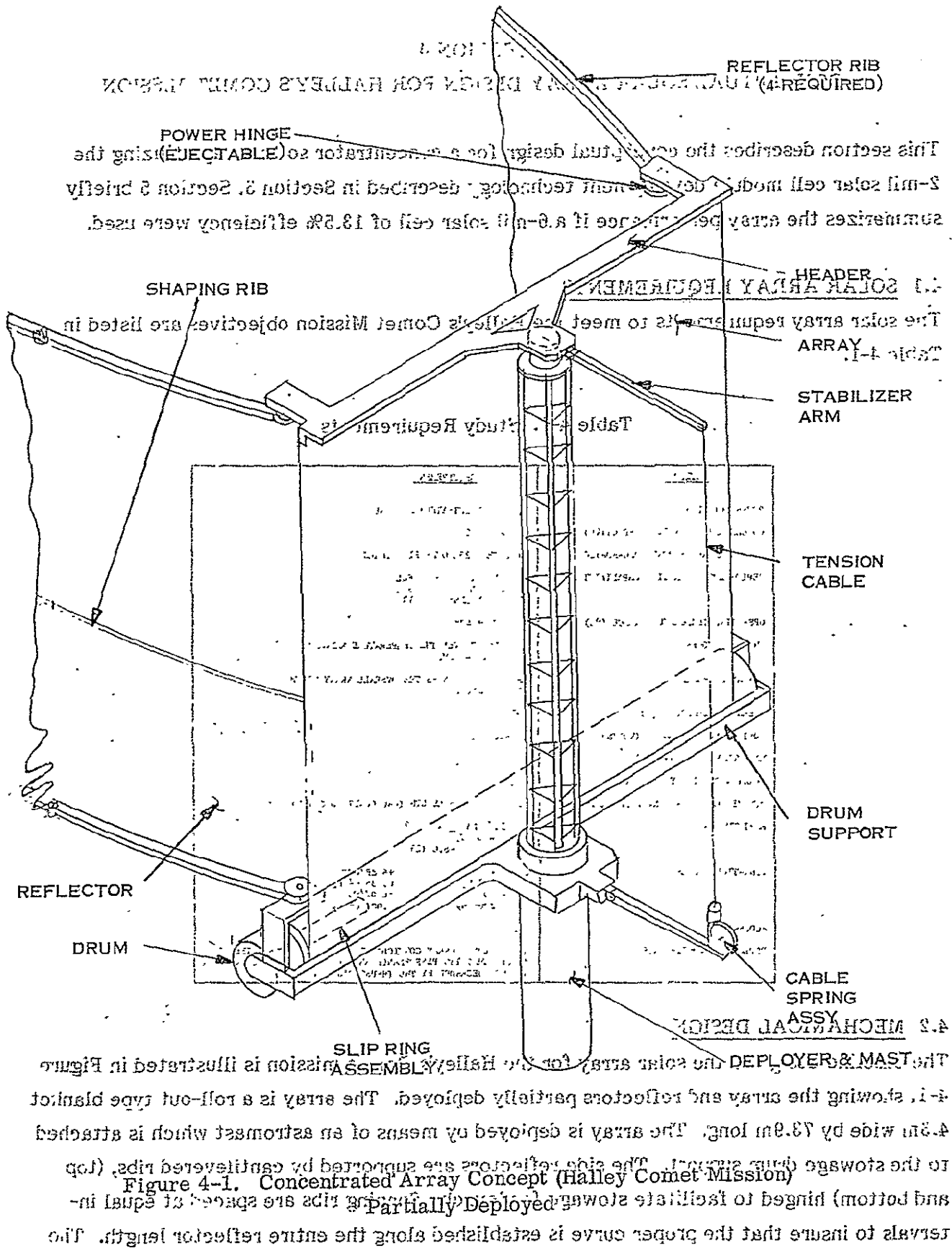
Table 4-1. Study Requirements

CATEGORY	REQUIREMENT
POWER BOL (MW)	60 (UNCONCENTRATED) AT 1 AU
CONCENTRATION RATIOS (EFFECTIVE)	1.8 AND 3.2
ALLOWABLE ARRAY POWER DEGRADATION	LESS THAN 25% OVER FIVE YEARS
DEPLOYMENT/RETRACTILE CAPABILITIES	DEPLOYMENT: FULL RETRACTION: 90% NO. OF CYCLES: 50
OPERATING TEMPERATURE RANGE (°C)	-130 TO +140°C
THERMAL SHOCKS	100 CYCLES OVER THE TEMPERATURE RANGE OF +120°C TO -190°C
FLATNESS PARAMETER	MAXIMUM 10° ACROSS THE OVERALL ARRAY WIDTH AND/OR LENGTH
OPERATING PRESSURE (TORR)	10 ⁻⁵
NOMINAL VOLTAGE RANGE (VOLTS)	200-400VDC
MAXIMUM VOLTAGE (VOLTS)	420VDC
ARRAY NATURAL FREQUENCY (Hz)	0.015
DYNAMIC PACKAGING ENVELOPE (METERS)	4.5 DIA × 11.8 LENGTH (HAC CONFIG DMC #20)
MAXIMUM LOADS (G's)	LONGITUDINAL ± 4.0 (X) YAW ± 4.0 (Y) PITCH ±10.0, -8.0 (Z)
VIBRATION LEVELS	25 - 100 Hz +6 dB/OCT 100 - 250 Hz 0.035 G ² Hz 250 - 500 Hz -6 dB/OCT 500 - 2000 Hz 0.009 G ² Hz
ACOUSTIC LEVELS (dB)	145
DEPLOYMENT CONSTRAINTS	THE DEPLOYED ARRAY CONFIGURATION SHALL BE CONSTRAINED TO ASSURE THAT ITS PERFORMANCE AND THE SPACECRAFT PERFORMANCE ARE NOT DEGRADED BY THE THRUSTER'S IO PLUME.

4.2 MECHANICAL DESIGN

The baseline design of the solar array for the Halley's Comet mission is illustrated in Figure 4-1, showing the array and reflectors partially deployed. The array is a roll-out type blanket 4.3m wide by 73.9m long. The array is deployed by means of an astromast which is attached to the stowage drum support. The side reflectors are supported by cantilevered ribs, (top and bottom) hinged to facilitate stowage for launch. Shaping ribs are spaced at equal intervals to insure that the proper curve is established along the entire reflector length. The

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extended reflector is hinged at the root to provide adjustment of the reflector assembly to two levels of concentration (i.e., effective concentration ratio of 1.8 and 3.6). The reflectors are moved by means of hinge motor assemblies directly attached at the root pivot point. These drive assemblies are mounted to the header (19)* and drum support (13)* with adapters so that the concentrator can be jettisoned at a specific point in the mission profile. The concentrator position for jettisoning is shown in Figure 4-2.

*Callouts refer to Figure 4-4.

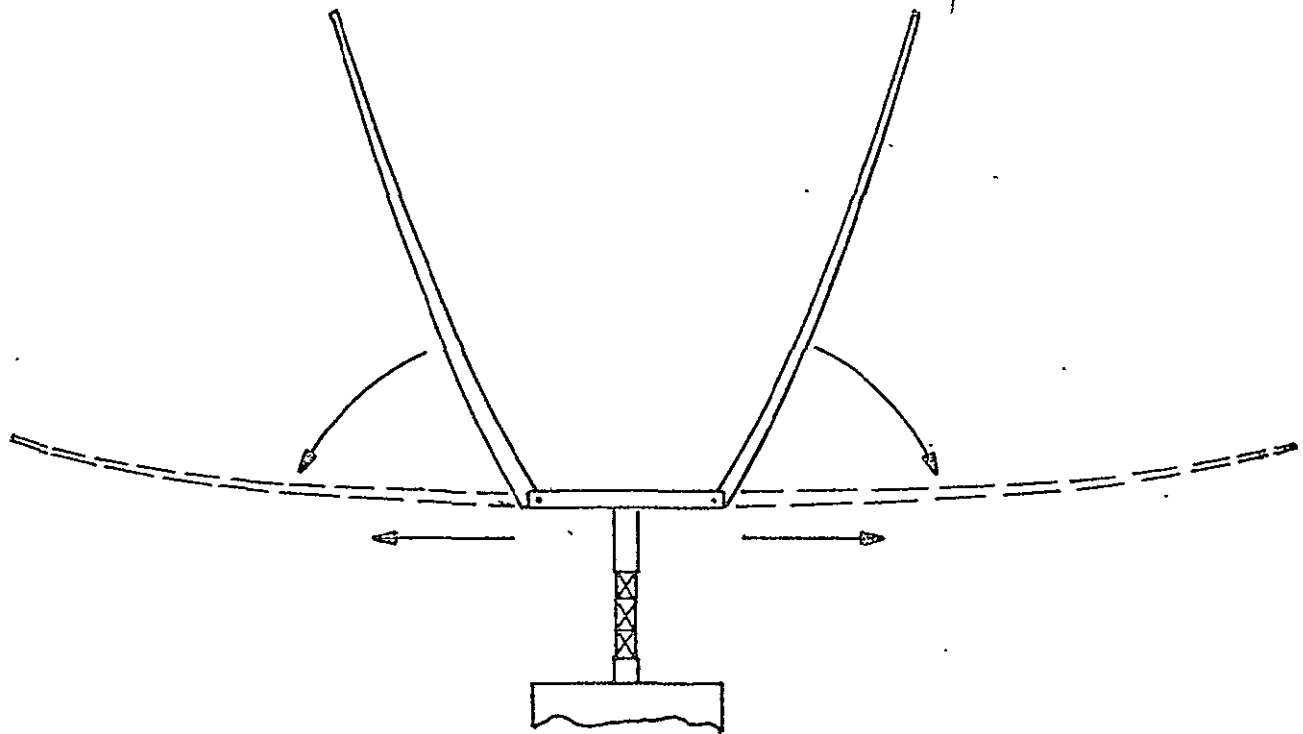


Figure 4-2. Jettison Position for Concentrator

The reflectors are rotated to bring their center of gravity in line with the direction of ejection (parallel to the drum axis). During this rotation, the tension in the stabilizer cable is reduced upon ground command to a lower value by a pyro release device in the tension cable assembly (18).

Size and Weight

The overall size of the deployed array is essentially 15m x 18.6m x 74 meters as shown in Figure 4-3. The entrance aperture of the concentrator is initially set at for a concentration ratio of 1.8 at 1 AU and opened to 18.6m for ratio of 3.8 at 4.5 AU. The total mass of the

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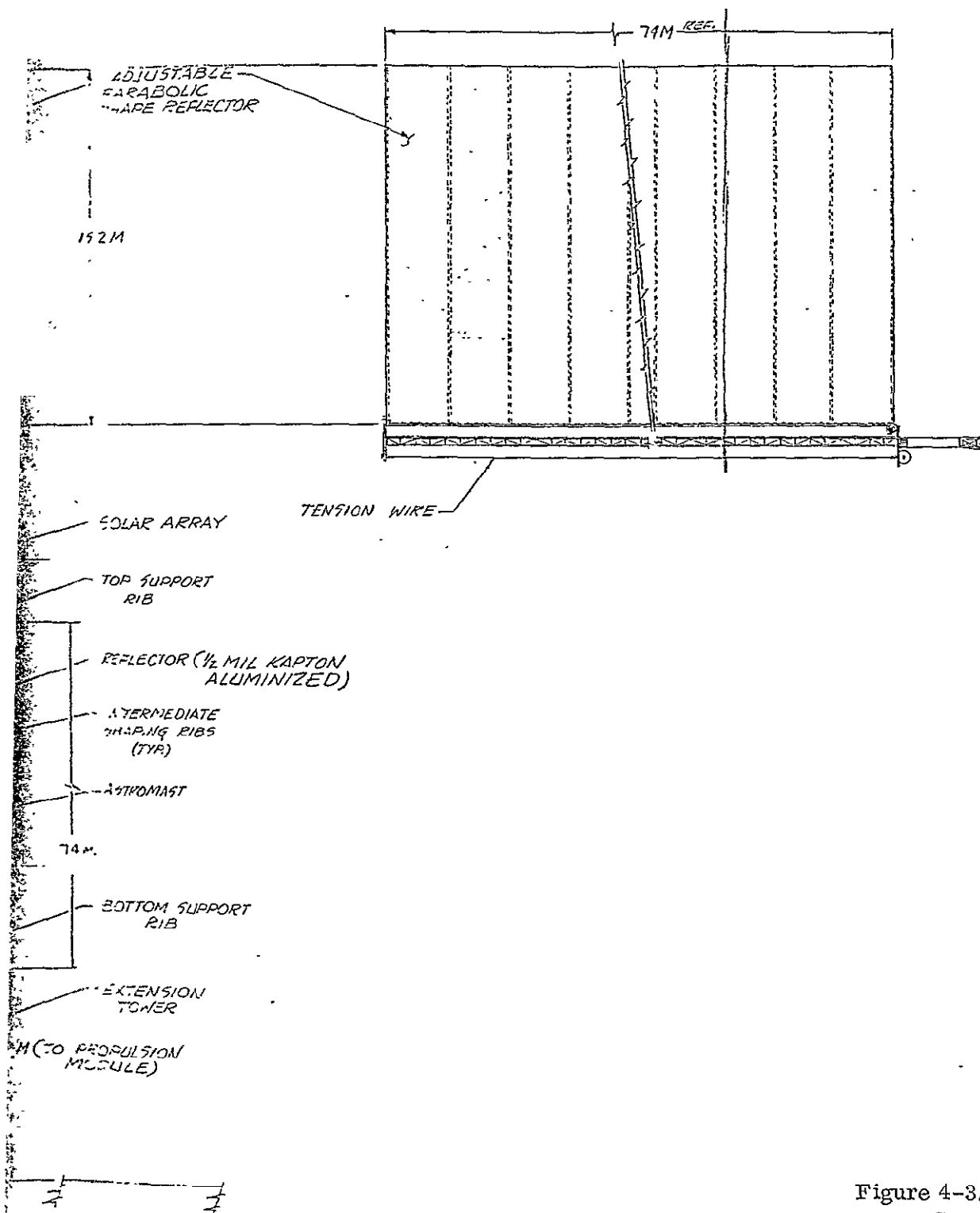
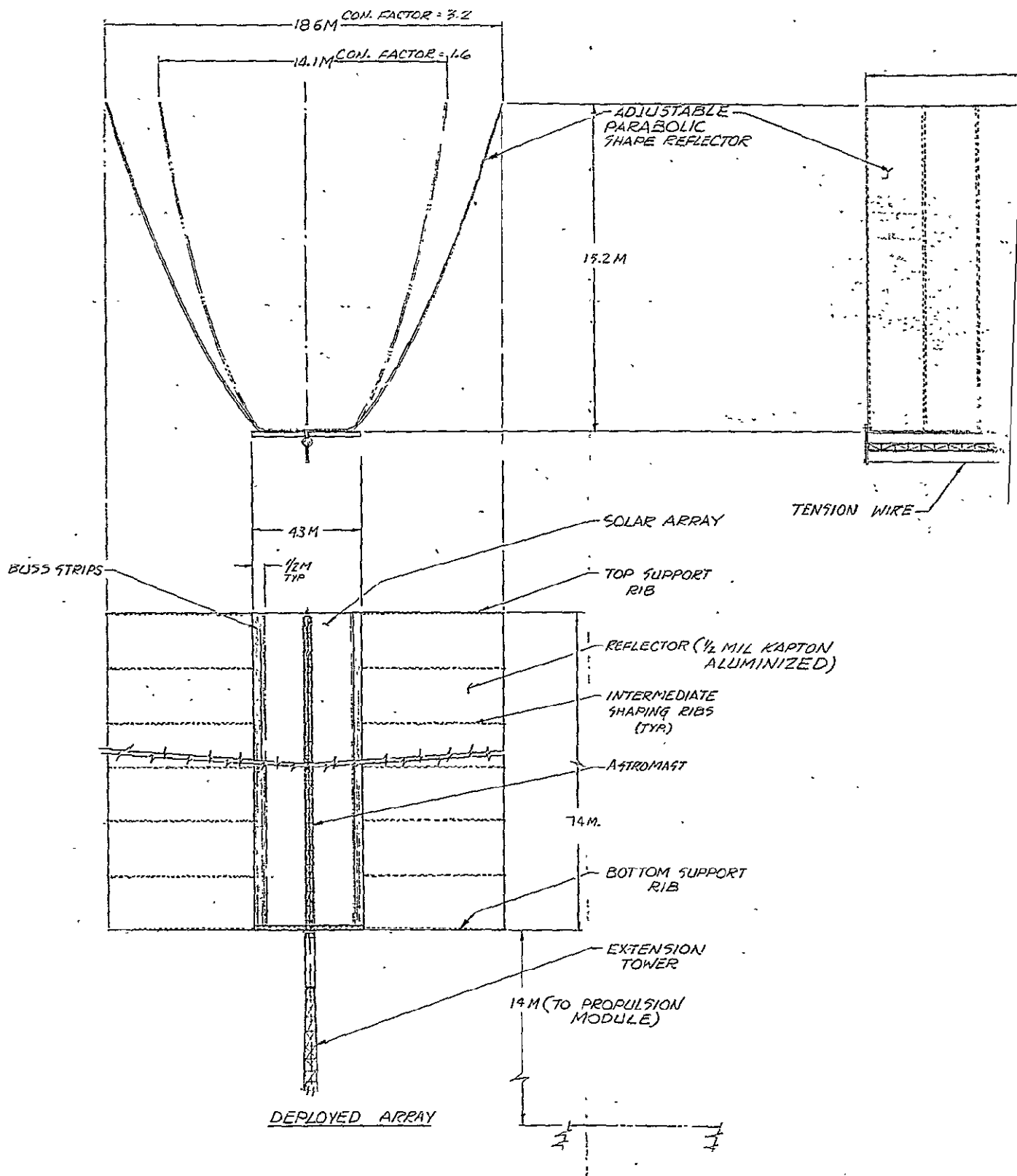


Figure 4-3. Concentrated Array
Concept (Deployed)



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baseline array including a boom to extend the array 14 meters from the spacecraft is estimated at about 386 Kilograms per wing. This value is based upon the use of thin 2-mil solar cells in a ultra-lightweight blanket which is nonretractable. A breakdown of the mass is given in Table 4-2 with item references given in Figure 4-4.

Table 4-2. Mass Summary (Articulated Parabolic Concentrated Concept)

Item No.	Item	Unit Mass KG	Quantity Per Wing	Baseline Design KG
	<u>Blanket (Electrical)</u>			
1.	Solar Cells	78×10^{-6}	596,960	46.56
2.	Substrate	.036/m ²	317.8 m ²	11.44
3.	Adhesive (1 mil RTV)	.01/m ²	243.8 m ²	2.44
4.	Cover Material (3 mil RTV)	.03/m ²	243.8 m ²	7.32
5.	Interconnects	25 mg	596,960	14.92
6.	Bus Strips	.144/m	73.9 m	10.6
7.	Slip Rings Assy	7.0	1	7.0
8.	Cable	.2	1	.2
9.	Connectors	.04	4	.24
10.	Switching Relays	.03	52	1.56
11.	Control Modules	.20	1	.20
	Sub Total			102.57
	<u>Blanket Support/Stowage</u>			
12.	Drum	5.93	1	5.93
13.	Drum Support	24.83	1	24.38
14.	Shaft & Bearings	3.67	2	7.34
15.	Mast	46.20	1	46.20
16.	Mast Deployer	39.3	1	39.3
17.	Stabilizer Arms	1	2	2.0
18.	Tension Wire Assy	.84	1	.84
19.	Header	6.0	1	6.0
20.	Blanket Tension Springs	.2	5	1.0
21.	Drum Drag Brake	.2	1	.0.2
	Sub Total			133.64
	<u>Concentrator</u>			
22.	Reflector (Kapton Film)	20	2	40.0
23.	Support Rib	13	4	42
24.	Shaping Rib (Inc. Flex Hinge)	.59	12	7.08
25.	Rib Folding Joint	1	16	16.0
26.	Rib Power Hinge	4	4	16.0
27.	Jetison Adapter	2.3	4	9.2
28.	Container Support	2.0	1	2.0
				132.28
29.	Misc. Hardware	-	-	5.0
30.	Extension Mast	12.9	1	12.9
	Total Mass	12.9		386.39

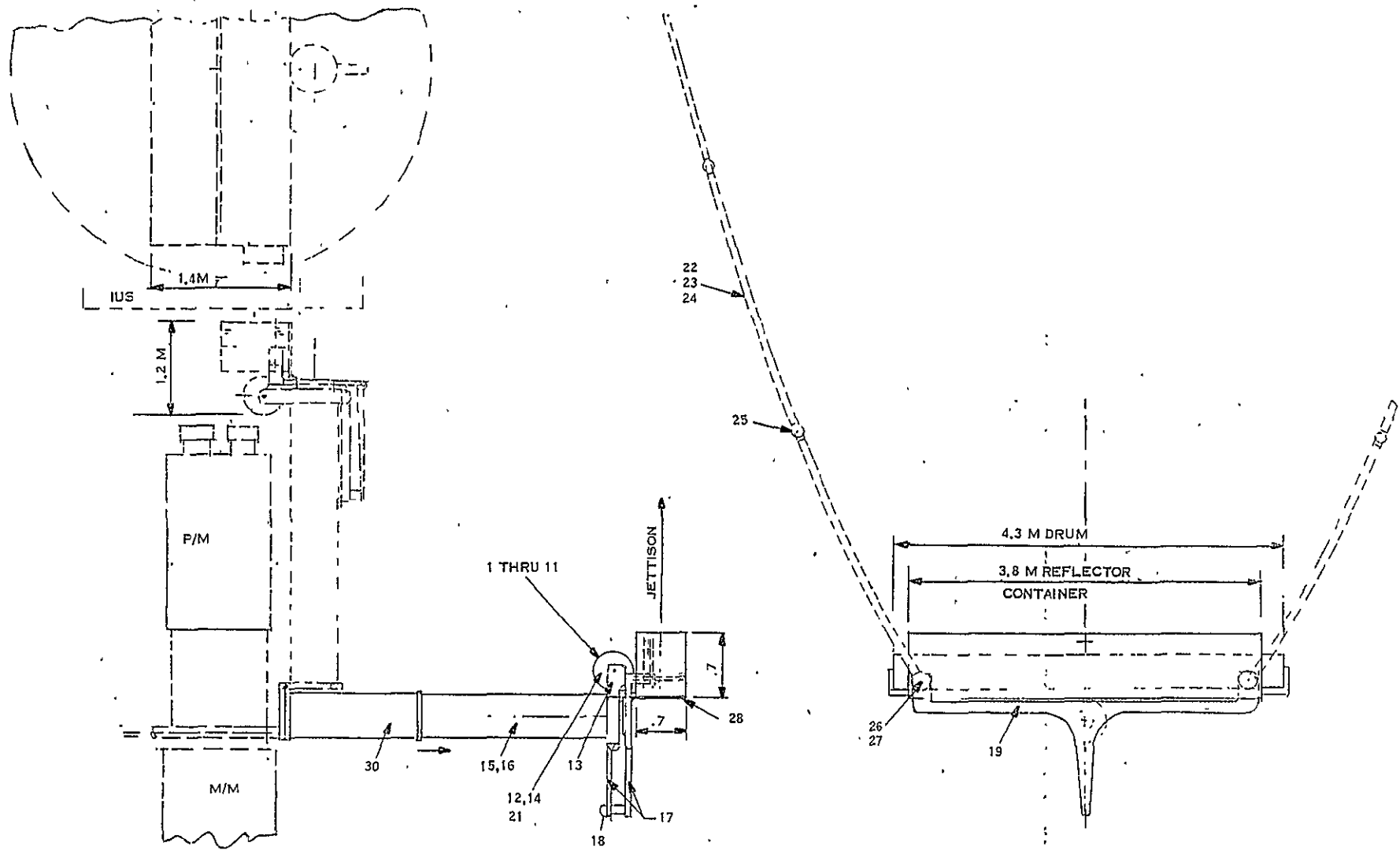


Figure 4-4. Solar Array Concept (Articulated CPC Reflector)

Structure and Tension

The primary structure of the array assembly is an astromast of about 20 inch diameter capable of taking a 100 lb axial load. The stiffening of the assembly results from the "V" formation of the concentrators.

4.2.1 MECHANICAL ELEMENTS

4.2.1.1 Canister and Mast

The extendible boom which deploys the array and concentrator is a coilable lattice boom of the type manufactured by Astro Research Corporation. The longeron and cross members are constructed with polyimide resin glass reinforced composite to withstand the higher temperatures (150°C) expected in this mission.

4.2.1.2 Slip Rings

The slip ring assembly consists of 26 power rings with returns capable of handling 20 amperes each and a number of small signal rings rated at 0.5 amps. The general configuration of the unit is shown in Figure 4-5.

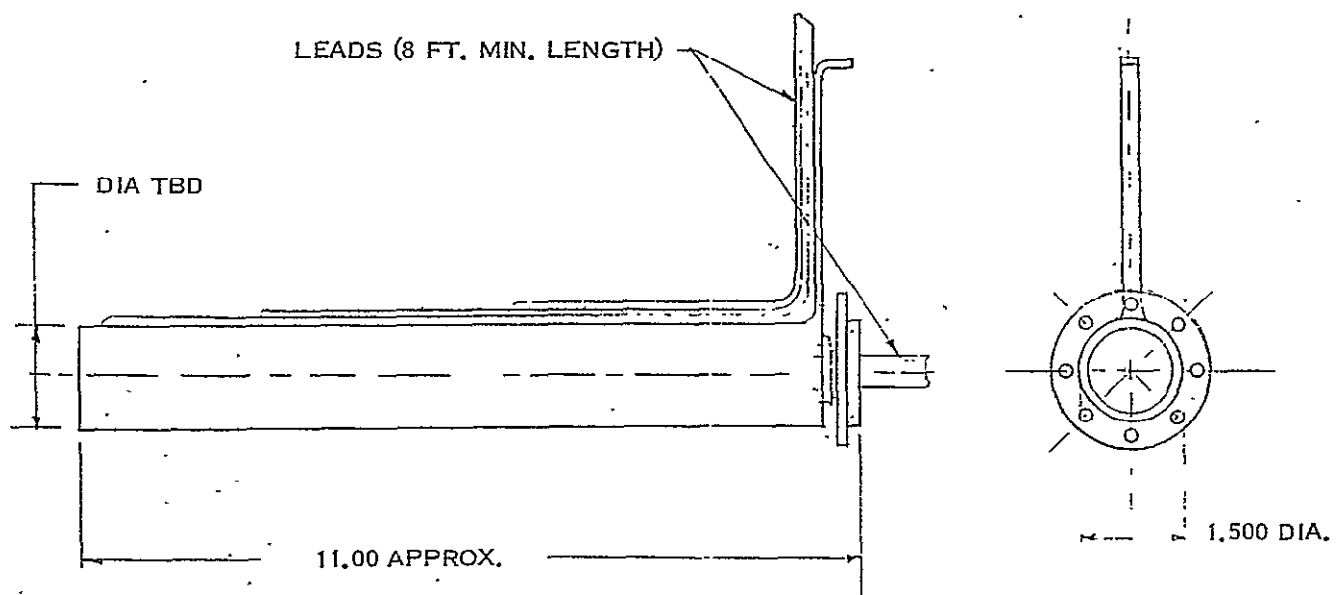


Figure 4-5. Slip Ring Assembly

4.2.1.3 Tensioning Devices

Two tensioning devices are needed to (1) establish a specified tension level in the blanket array when fully developed, and (2) maintain a tension in the concentrator film in the longitudinal direction. For the blanket tension in the non-retractable version, a short travel rotary or linear spring comes into play near the end of full extension to establish the desired tension with low gradient characteristic to allow for thermal expansion. During extension, a low tension is produced in the blanket by means of a lightweight brake on the drum. Since rotary spring motors such as the negator motor become very heavy for the long extension lengths involved in the Halley mission, a considerable weight saving can be realized with the brake approach.

Concentrator tension and tension on the stabilizing cable which compensates for the movement at the top of the mast caused by the concentrator and blanket tension are also established by springs which become effective near the end of the deployment cycle. The cable spring assembly is equipped with a pyro release device to reduce that tension to a lower value after jettisoning the concentrator.

4.2.1.4 Concentrators

The concentrators are composed of thin aluminized Kapton film (1/2-mil) stretched over supporting ribs which are articulated in four points to permit stowage in a small volume. The ribs are curved to generate the desired parabolic shape at the ends of the reflector. This shape is insured along the reflector by means of six (6) shaping ribs of very lightweight "T"-section members bonded to the film to maintain the desired curvature. These ribs are also articulated with flexure hinge points to accommodate folding.

A concept for the support rib hinge joints is shown in Figure 4-6. A torsion spring torque the arms into position against a pin stop. The deployed position is held by means of a spring actuated cam lock which automatically snaps into its final position. The sequence of deployment of the concentrator along with the array is illustrated in Figure 4-7. Mechanical latches holding the bundle in the stowed configuration are sequentially tripped by the rib unfolding action to control the deployment sequence of the concentrator.

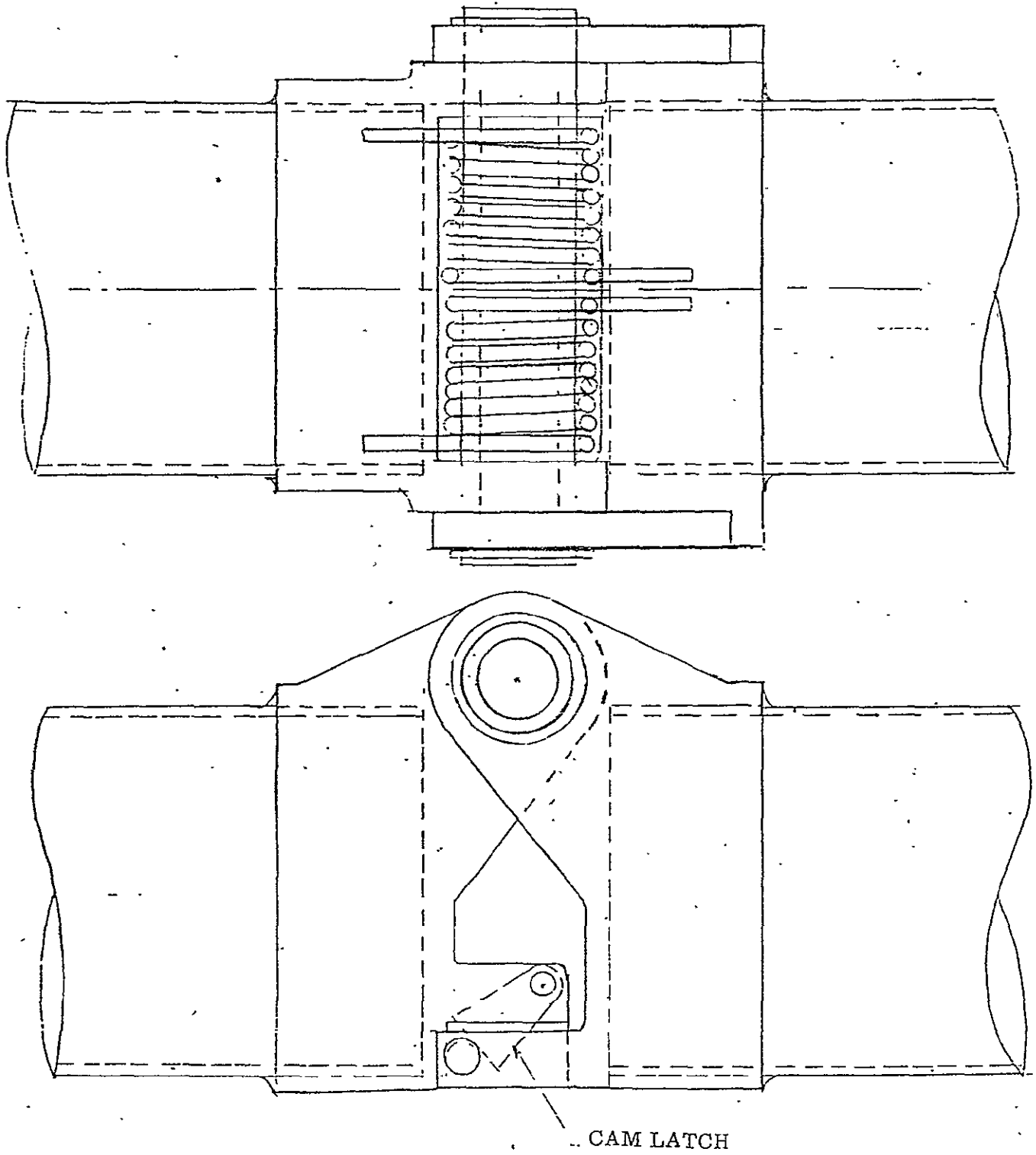


Figure 4-6. Rib Hinge Concept

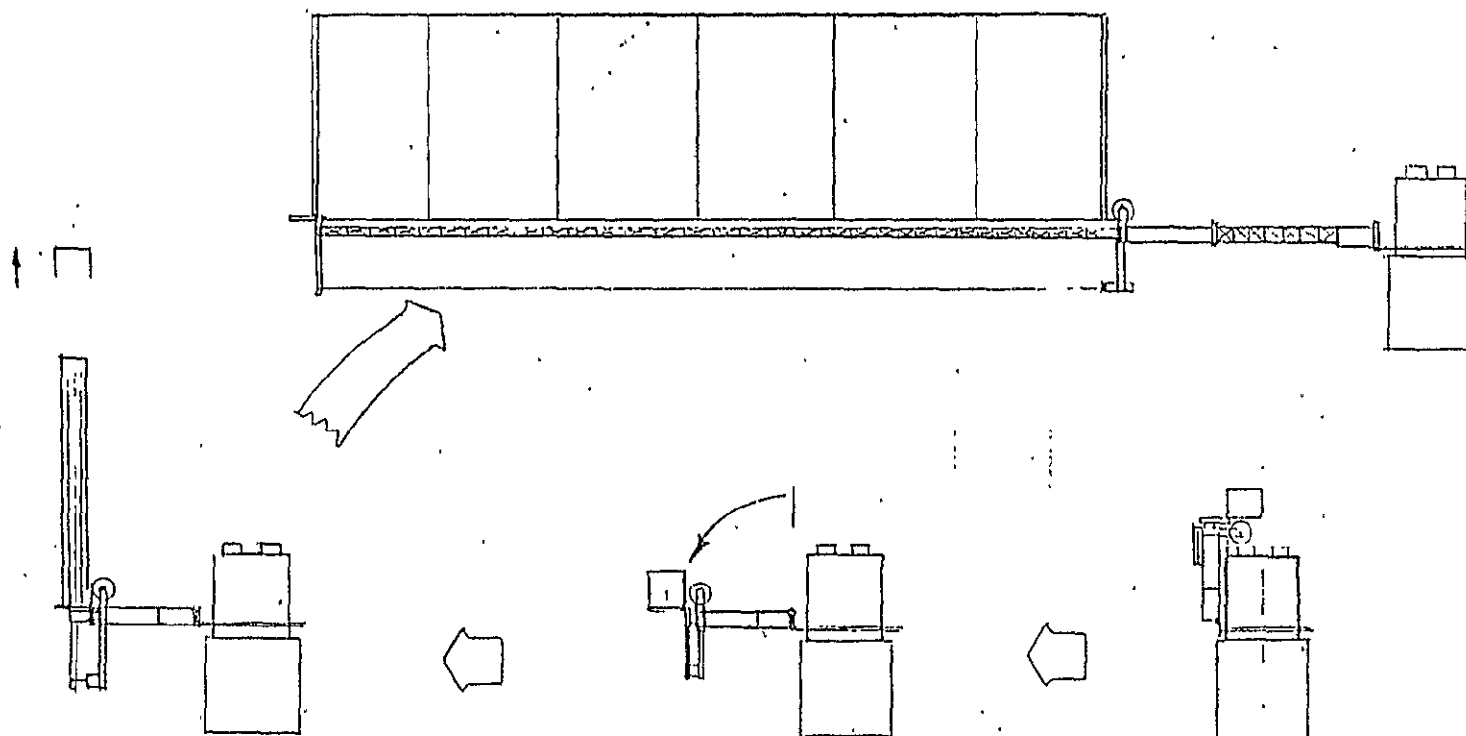


Figure 4-7. Deployment Sequence

4.2.1.5 Materials

It is expected that graphite reinforced composites will be used extensively in this concept. Thin wall composite tubing is considered to be a prime candidate for the concentrator support ribs because of its high stiffness to weight ratio. Beryllium hinge tube fittings and drum support structure will be chosen where necessary to meet the weight goal. Carbon composites will also be given consideration in the support structure.

4.2.1.6 Mass Summary

The total mass of the system as discussed in Paragraph 4.2 is estimated to be 773 Kg. The breakdown of weights includes 30 items as shown in Table 4-1.

4.3 ELECTRICAL DESIGN

This section describes the electrical design for the concentrator solar array proposed for the Halley's Comet Mission. Maximum use of the technology developed for two-mil cells as described in Section 3 of this report has been incorporated into the design.

4.3.1 SOLAR CELL CIRCUITS

The smallest replaceable group of solar cells incorporated into the blanket design is a matrix of 28 solar cells, connected 7 in series by 4 in parallel. Each solar cell is 2 Cm x 2 Cm x 0.002 inch in size. Invar interconnects, as previously described, are welded to the silverized P-surface of one row of cells, and to the N-surface tabs of the adjacent layer. This is depicted in Figure 4-8. Interconnect tabs at the top and bottom of the circuit will be trimmed off as appropriate to permit the circuits to be interconnected alternately as shown in Figure 4-9. Each solar cell circuit produces 1.41 watts at the maximum power point (1 AU, AMO, 55°C) and develops a maximum power voltage of 2.66 volts.

4.3.2 SOLAR CELL MODULE

A solar cell module consists of 41 circuits connected in series across the width of the blanket as shown in Figure 4-10. Each circuit is orientated 180 degrees from its adjacent circuit to alternate the direction of current flow and thereby minimize the magnetic fields generated. The 41 series circuits represent a total of 1148 cells connected 287 in series by 4 in parallel. Each module produces 57.7 watts at the maximum power point (1 AU, AMO, 55°C) and develops a maximum power voltage of 109 volts.

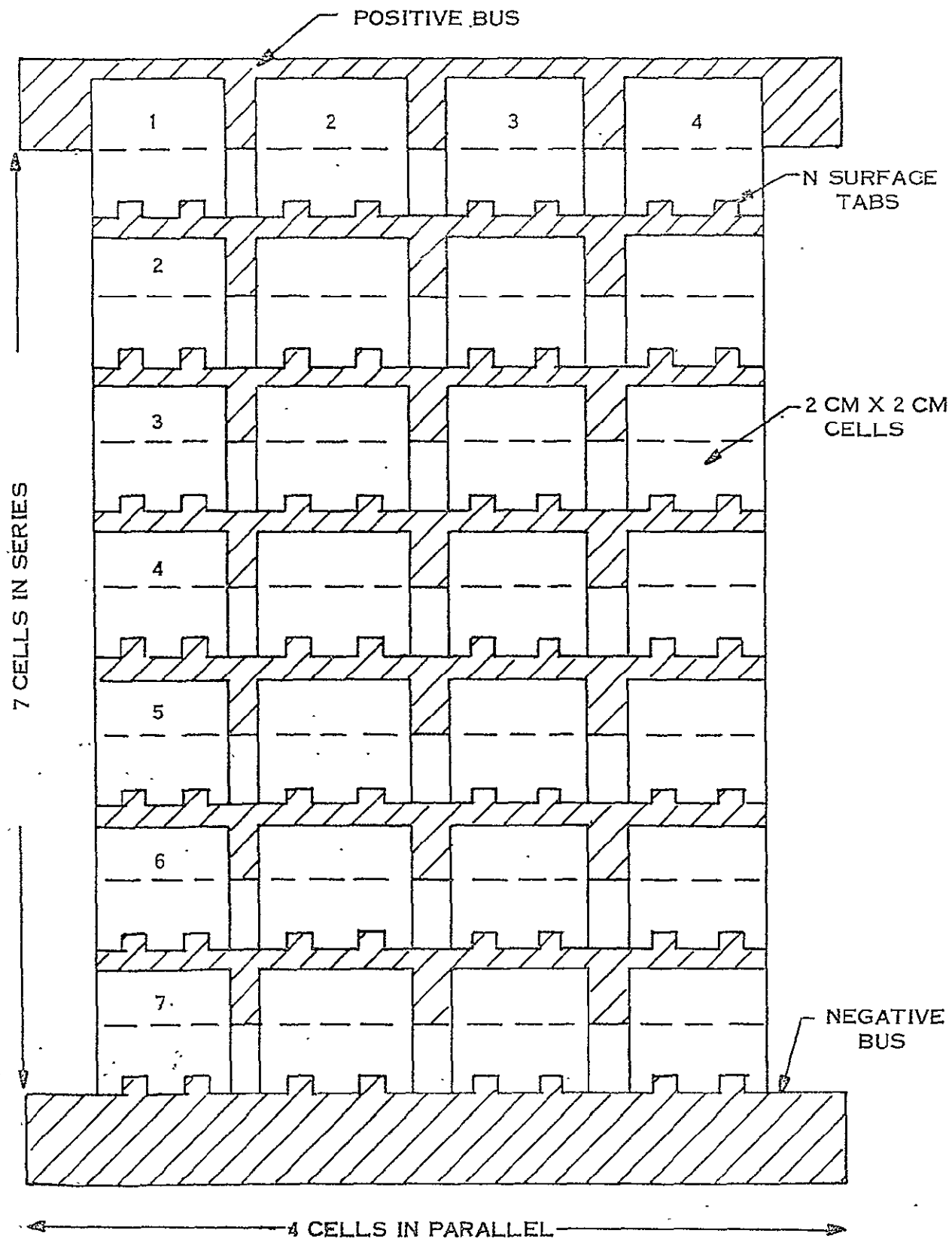


Figure 4-8. Circuit Layout (7S by 4P)

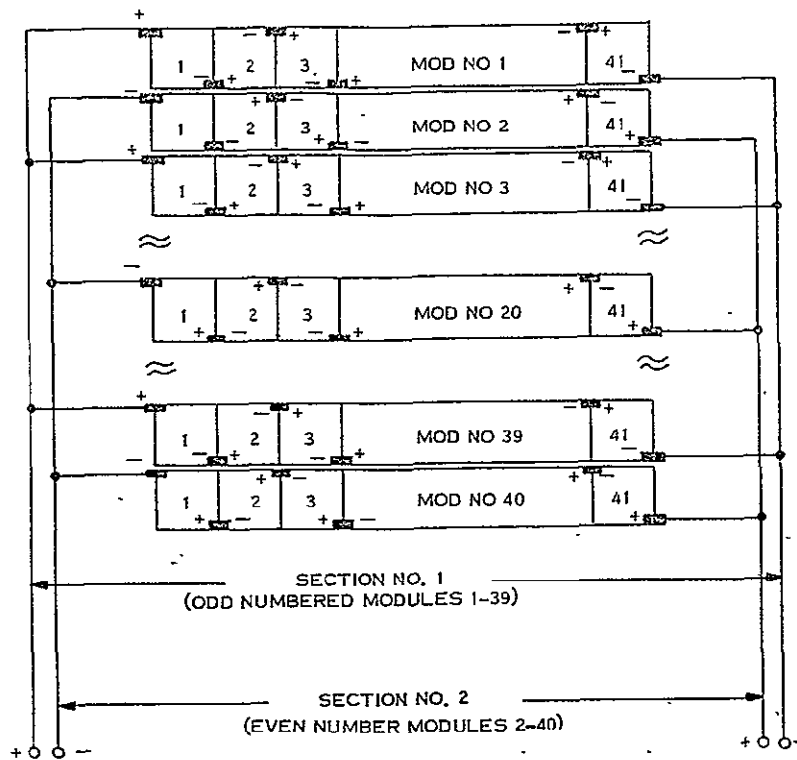


Figure 4-9. Circuit Module Interconnections

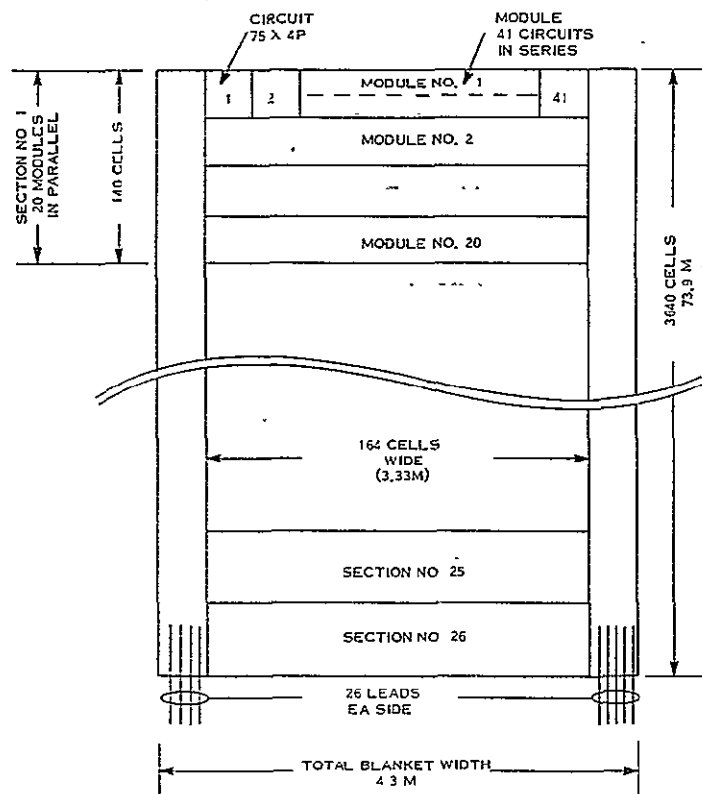


Figure 4-10. Blanket Layout

4.3.3 Solar Cell Section

A solar cell section is the smallest area of the total blanket from which external cabling is routed to the spacecraft. Each section is composed of 20 alternate modules connected in parallel. This permits current flow across the width of the blanket to be in opposite directions for adjacent modules and thereby minimize the magnetic fields generated. The 20 module in each section represent 22,960 solar cells connected 287 in series by 80 in parallel. This produces 1155 watts at the maximum power point (1 AU, AMO, 55°C) and a maximum power voltage of 109 volts.

4.3.4 Solar Array Blanket

Each solar array blanket (or wing) contains 26 sections as shown in Figure 4-10. The power from each section is brought out on two flat aluminum conductors running along the sides of the blanket. The conductors are sized in cross section according to the length of their run to equalize the section voltages at the array output. Approximately 0.5 meters of blanket width is allocated on each side of the blanket to accommodate the 26 flat aluminum conductors. The conductors are positioned underneath the concentrators so they will not be exposed to concentrated sunlight. The maximum expected current for each conductor is 20 amperes (1 AU, CR=1.8, AMO, 110°C).

The overall blanket size is 4.3 meters wide by 73.9 meters long. The 596,960 cells per wing occupy an area 3.3 meters wide by 73.9 meters long. A cell-to-cell spacing of 0.03 Cm was assumed in the sizing.

4.3.5 Mode Switching

Each solar array wing is composed of 26 sections. The power from each section is routed along the blanket sides via flat aluminum cables to the mode switching relays located within the array drum. The relays connect the individual sections into two groups of nine sections in parallel and two groups of four sections in parallel. The four groups are then interconnected into one of two configurations as shown in Figure 4-11. The array output then passes through the slip rings located within the drum onto the power bus. The two mode switching configurations are necessary to maintain the array output voltage between 200 and 400 VDC. A power controller can be added between the array output and the bus if additional regulation is required.

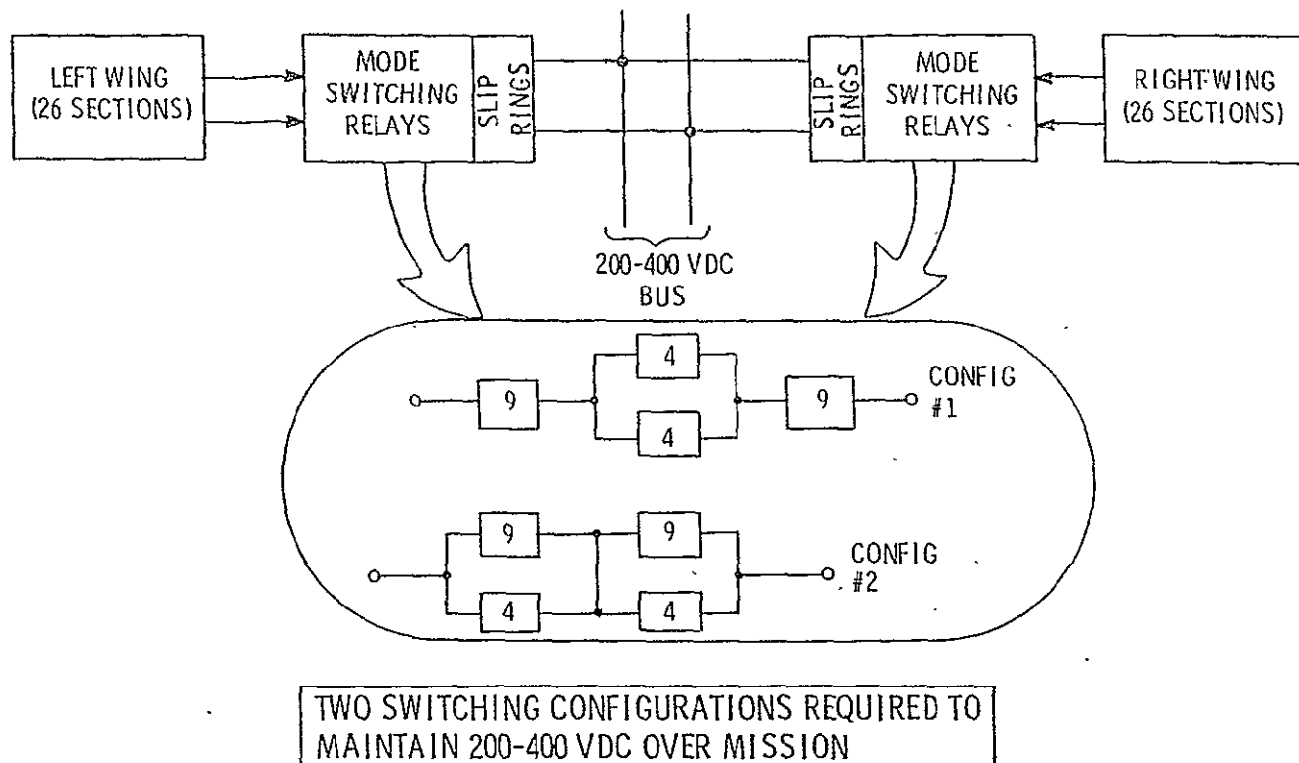


Figure 4-11. Mode Switching Diagram

4.3.6 System Performance

A preliminary estimate of the system performance of the solar array has been made utilizing the Halley's Comet Mission trajectory shown in Figure 4-12. The array power, voltage, and temperature as a function of distance from the sun and concentration ratio have been calculated and are described in this section of the report. Of equal importance is the impact on power degradation due to the radiation environment. Although the analytical activities to date in this area have been only cursory, it will also be addressed.

4.3.7 Mission Trajectory

The mission trajectory used to estimate the array performance is shown in Figure 4-12. After launch at 1.0 AU, the spacecraft travels outbound to a maximum distance of 4.5 AU over a time period of approximately 750 days. At 4.5 AU, the spacecraft moves inbound along the orbit of the comet for rendezvous at about 1.1 AU. The time period for the spacecraft to travel from 4.5 AU to 1.1 AU is about 530 days. Therefore, rendezvous with the comet is about 1280 days after launch ($3\frac{1}{2}$ years). After rendezvous, the spacecraft follows the comet reaching a minimum sun distance of 0.6 AU.

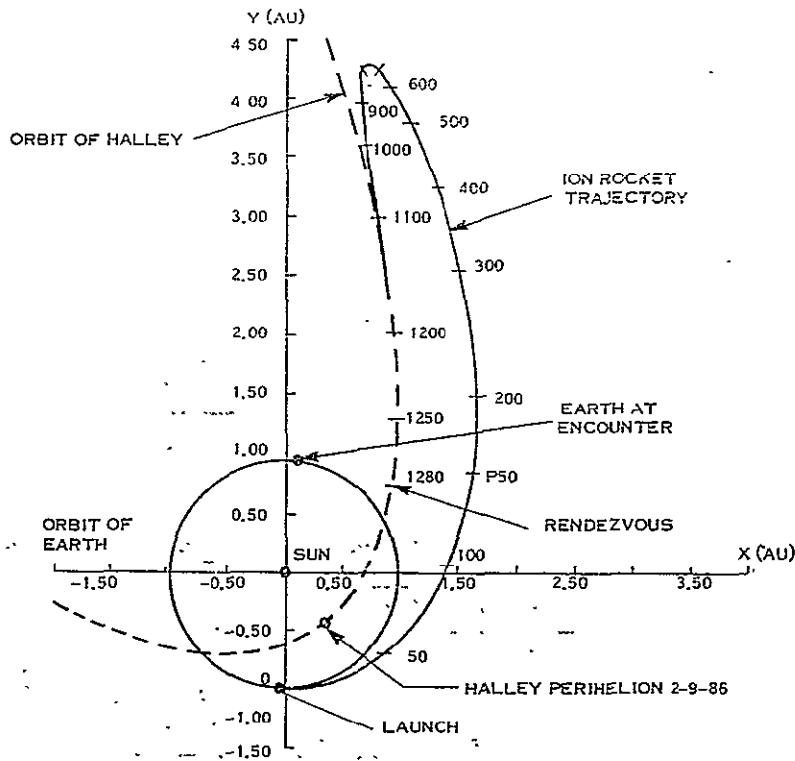


Figure 4-12. Halley Rendezvous Trajectory (Ecliptic Plane Projection)

4.3.8 Array Power Performance

The basic building block for the Halley's Comet solar array is a 2 Cm x 2 Cm x 0.002 inch solar cell having an efficiency of 60 mW at 28°C (11.1%). Estimates of cell power were made using the JPL test data (JPL IOM #341-018A, "Parametric Testing of Solarex 50 Micron Solar Cells", April 13, 1977, Mr. Bruce Anspaugh), and upgraded the efficiency from those tested (9.96%) to the present 11.1%. Effective concentration ratios of 3.2 and 1.8 were used to establish the solar incident energy impinging on the solar cells (geometric ratios are 4.6 and 2.0 respectively). These data, along with the solar cell temperature estimates over the Halley's Comet Mission, were used to calculate array power.

Table 4-3 summarizes the results of the analysis relating to array power and voltage as a function of distance from the sun. Effective concentration ratios of 3.2 and 1.8 were used. The solar incident energy falling upon the cells was calculated as:

$$\text{Incident Energy} = \frac{\text{solar constant (135.3 mW/cm}^2\text{)}}{(\text{Au distance})^2}$$

Table 4-3. Array Performance Over Halley's Comet Mission Trajectory

AU Distance	Concentration		Incident Energy	Array Temp.	Cell Power	Cell Voltage	Undegraded Array Power	Section Voltage	Array Voltage With Switching	Switch Config.
	Ratio	Equiv AU								
1	1	1	135.3 mW/Cm ²	55°C	50.3mW	0.38VDC	60KW	109VDC	327VDC	1
1	1.8	0.75	243.5 mW/Cm ²	110°C	58.6mW	0.30VDC	70KW	86VDC	258VDC	1
1.1	1.8	0.82	201.2 mW/Cm ²	85°C	38.1mW	0.32VDC	69.4KW	92VDC	276VDC	1
1.1	1	1.10	111.8 mW/Cm ²	50°C	18.4mW	0.38VDC	57.8KW	109VDC	327VDC	1
1.5	1.8	1.12	108.2 mW/Cm ²	45°C	15.2mW	0.40VDC	54KW	115VDC	344VDC	1
1.5	3.2	.81	192.4 mW/Cm ²	90°C	57.3mW	0.335VDC	68.4KW	96VDC	288VDC	1
2.0	3.2	1.12	108.2 mW/Cm ²	10°C	14.9mW	0.404VDC	53.6KW	116VDC	318/232VDC	1/2
2.8	3.2	1.57	55.2 mW/Cm ²	0°C	28.3mW	0.50VDC	33.8KW	144VDC	287VDC	2
3.0	3.2	1.68	48.1 mW/Cm ²	-15°C	24.6mW	0.540VDC	29.4KW	156VDC	310VDC	2
4.0	3.2	2.23	27.1 mW/Cm ²	-50°C	14.7mW	0.620VDC	17.6KW	178VDC	356VDC	2
4.5	3.2	2.50	21.4 mW/Cm ²	-72°C	12.9mW	0.680VDC	15.4KW	195VDC	390VDC	2

When using solar concentrators, the cells behave as though they were closer to the sun (higher incident energy) than they actually are. The "equivalent AU" listed on the table is a measure of that effect. The equivalent AU was calculated as:

$$\text{Equiv AU} = \left[\frac{\text{Solar Constant}}{\text{Incident Energy}} \cdot 1/2 \right]$$

As can be seen on the table, when the solar array is actually at 4.5 AU, but has a concentration of 3.2, the effective AU is 2.5. Since the solar cell power varies inversely with the square of the distance, the power output is increased significantly at far distances from the sun by using concentrators.

By using the incident energy along with the corresponding cell temperature, the cell power and voltage (at maximum power point) was determined using the JPL test data previously mentioned. The cell power was ratioed upward by 11.1/9.96 to account for the present cell efficiency. The "cell power" and "cell voltage" values shown on Table 4-2 were thus determined. The undegraded array power is the product of the total number of cells times the cell power (no losses assumed at this point).

As described in Paragraph 4.3.3, a solar cell section is composed of 20 modules connected in parallel. Each module consists of 41 circuits connected in series. Each circuit is a 7 series by 4 parallel celled building block. Therefore, the voltage developed per section (same as module) is 7 cells/circuits x 41 circuits, or 287 cells in series. The column labeled "section voltage" is 287 times the cell voltage. The cell voltage was taken directly from the JPL test data. The switching configurations described in Paragraph 4.3.5 either doubles (Configuration #2) or triples (Configuration #1) the voltage from each section. The column labeled "Array Voltage with Switching" on Table 4.2 shows the resulting values.

Figure 4-13 shows a plot of the total undegraded array output power as a function of AU. From initial array deployment at 1.0 AU to about 1.5 AU, the parabolic concentrators are set for an effective concentration ratio of 1.8 to 1.5 AU, the ratio is changed from 1.8 to 3.2. The concentration ratio remains at 3.2 until the spacecraft completes its outbound

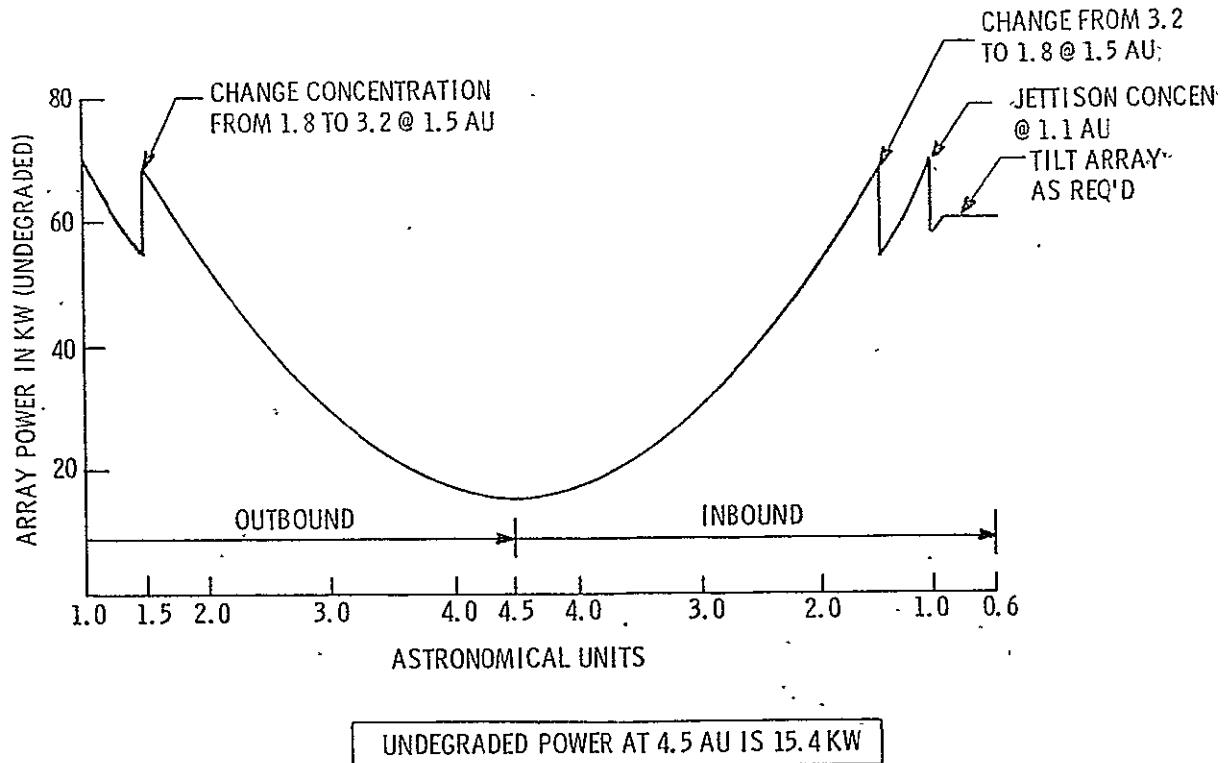
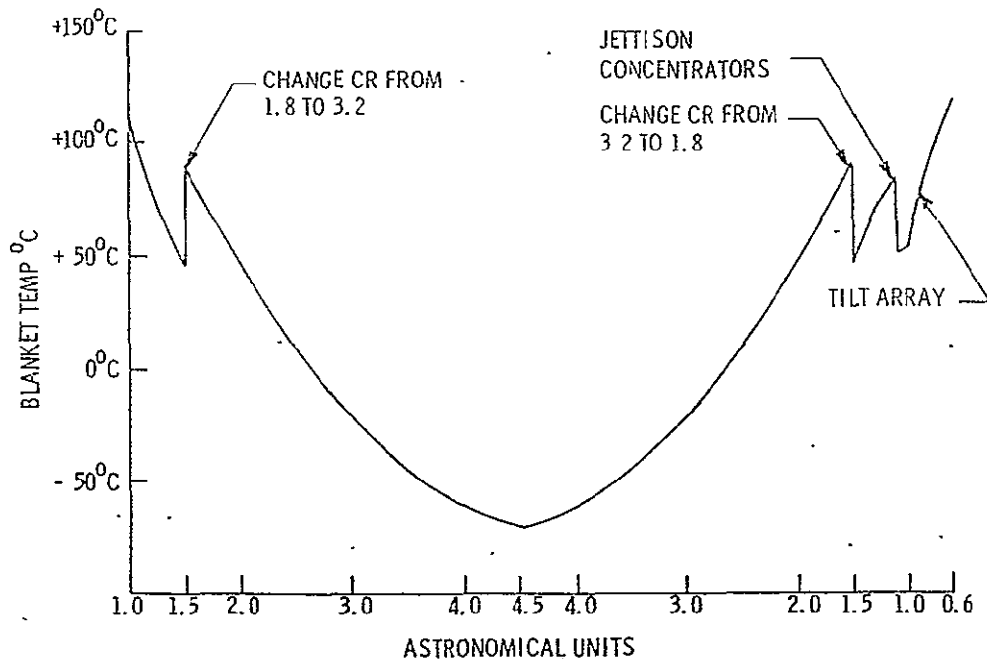


Figure 4-13. Undegraded Power vs AU

journey and returns inbound to 1.5 AU (approximately 1135 days). At 1.5 AU, the concentrators are moved back to the 1.8 ratio position until just prior to comet rendezvous (approximately 1.1 AU). At this point, the concentrators are jettisoned as their usefulness has terminated. In order to maintain temperature control (120°C maximum), the array can be tilted as the spacecraft travels inbound from about 0.8 AU. Figure 4-14 shows the array temperature profile.

The total undegraded array output power varies from 70kW at 1 AU to 15.4kW at 4.5 AU, as seen on Figure 4-13. If an overall degradation of 12% is assumed, those values will drop to 61.6kW and 13.6kW, respectively. A requirement to drive six ion engines at 2kW per engine at 4.5 AU will result in a power margin of 1.6kW for the degraded array.



BLANKET TEMPERATURE RANGE OVER MISSION IS -72°C TO $+120^{\circ}\text{C}$

Figure 4-14. Array Temperature vs AU

4.3.9 ARRAY VOLTAGE PERFORMANCE

Using the values established for cell voltage listed on Table 4-3 and the switching scheme described in Paragraph 4.3.5, a plot of array voltage over the Halley's Comet Mission was developed and is shown in Figure 4-15. The array voltage output varies between 232 VDC and 390 VDC using the switching points as shown. Configuration #1 is used for sun distances less than 2 AU and configuration #2 for sun distances greater than 2 AU. The voltage range shown falls well within the specification limits of 200 to 400 VDC.

4.3.10 RADIATION ANALYSIS

A radiation analysis was conducted using the electron and proton fluence listed in Table 4-4 for the Halley's Comet Mission (Ion Drive). The fluence levels stated at 50% probability were doubled for the analysis. The results show a maximum power degradation of 5% over the mission. This value was obtained by using the JPL supplied test data of power loss versus the damage equivalent normally incident (DENI) electron fluence at 1 MEV. This value excludes the effect of UV Radiation.

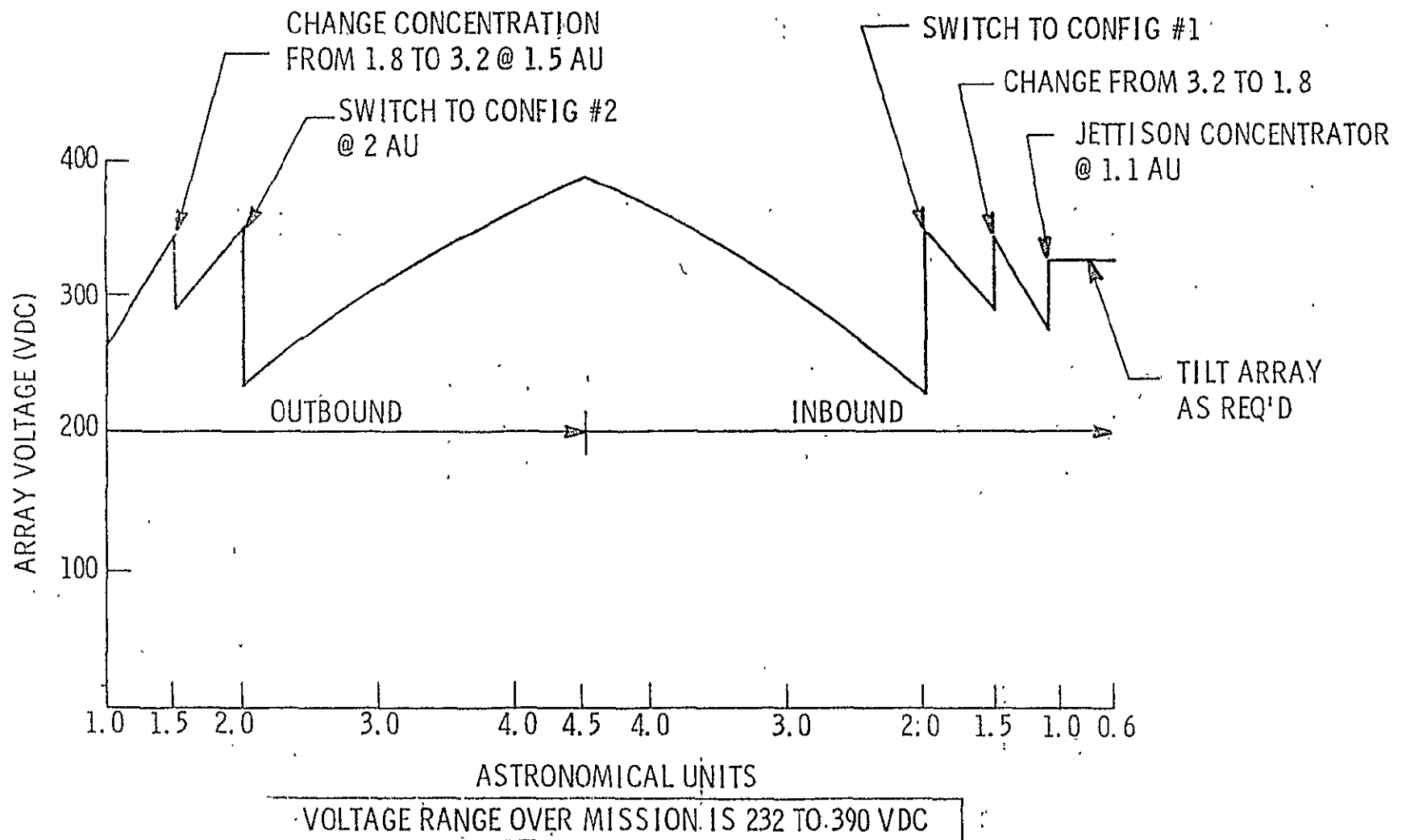


Figure 4-15. Array Voltage vs AU

Table 4-4. Fluences for Halley's Comet/Ion Drive Mission

PARTICLES	ENVIRONMENT	ENERGY	INTEGRAL FLUENCE, F (cm ⁻²)			
			PROBABILITY THAT F IS NOT EXCEEDED ⁽⁴⁾			
			50%	75%	90%	95%
INTERPLANETARY PROTONS	SOLAR WIND ⁽²⁾	0	3.9 (15)			
		900 eV	3.9 (15)			
		1 keV	3.1 (15)			
	INTERMEDIATE ENERGY PROTONS	10 keV	6.2 (13)			
		100 keV	1.2 (12)			
		1 MeV	2.5 (10)	2.5 (10)	2.5 (10)	2.5 (10)
		1.5 MeV	1.3 (10)	1.3 (10)	1.3 (10)	2.0 (10)
		3.0 MeV	4.0 (9)	4.0 (9)	8.5 (9)	1.2 (10)
		7.0 MeV	2.5 (9)	2.5 (9)	5.1 (9)	7.6 (9)
	SOLAR PROTON EVENTS AND COSMIC RAYS	10 MeV	1.5 (9)	2.1 (9)	4.4 (9)	6.0 (9)
		30 MeV	4.2 (8)	9.1 (8)	1.8 (9)	2.3 (9)
		60 MeV	3.1 (8)	4.6 (8)	6.9 (8)	8.7 (8)
		100 MeV	2.8 (8)	3.1 (8)	3.6 (8)	4.0 (8)
		1000 MeV	1.9 (8)	1.9 (8)	1.9 (8)	1.9 (8)
INTERPLANETARY ELECTRONS	SOLAR WIND ⁽³⁾	0	1.5 (16)			
		10 eV	1.5 (16)			
		20 eV	1.2 (16)			
		50 eV	4.0 (15)			
	INTERMEDIATE ENERGY ELECTRONS (SOLAR AND JOVIAN)	100 eV	1.0 (15)			
		1 keV	1.0 (13)			
		10 keV	1.0 (11)			
		100 keV	1.0 (9)			
		1 MeV	8.0 (7)			
	COSMIC RAYS	10 MeV	1.9 (7)			
		100 MeV	1.8 (7)			
		1000 MeV	6.4 (6)			

SECTION 5

OPTIONAL SOLAR ARRAY DESIGN

The solar array design described in Section 4 of this report utilized 2 Cm x 2 Cm x 0.002 inch solar cells having a power efficiency of 11.1% at 28°C. The optional design described in this section utilizes 2 Cm x 2 Cm x 0.006 inch solar cells having a power efficiency of 13.5% at 28°C. For the same power output, the increase in efficiency means that fewer cells are required and therefore a smaller overall blanket size. However, using cells 3-times thicker results in additional cell mass. As will be seen, these offsetting mass factors nearly compensate one another in the overall system. The principal description of this optional solar array was determined by ratioing appropriately from the baseline described in Section 4.

5.1 NUMBER OF CELLS REQUIRED

The baseline design utilizes 596,960 solar cells per wing to achieve 60 kW at 1 AU, 55°C with no concentration. By ratioing the number of cells by the power efficiencies:

$$\frac{11.1}{13.5} \times 596,960 = 490,834$$

The optional design requires 490,834 cells per wing to achieve the same power output at 13.5% efficiency.

5.2 ARRAY SIZE

The optional design maintains the same overall blanket width and concentrator height. Therefore, the 490,834 cells will be accommodated in an area 164 cells wide by 2993 cells long.

Using the same cell spacing (0.03 Cm), the array length will be:

$$2993 \text{ cells} \times 2.03 \frac{\text{Cm}}{\text{Cell}} = 60.7 \text{ meters}$$

This decrease in length from the baseline of 73.9 meters to 60.7 meters for the blanket, concentrators, and mast, affords a reduction in weight, as does the fewer number of cells required.

5.3 ARRAY WEIGHT

The optional solar array weight has been estimated by ratioing appropriately from the detailed weight estimates determined for this baseline. The weight breakdown is shown in Table 5-1. The total weight of the optional array design is nearly the same as that for the baseline for the same power output. This is because the higher cell efficiency permits using fewer of them and thus the array size is reduced. This weight reduction is closely offset by the increased weight due to the larger cell thickness. The 6-mil cell weight was calculated by adding 4-mils of silicon to the baseline 2-mil cell. It assumes the metallization, grids, weld tabs, etc. are the same for both cells. A silicon density of 2.4 grams/Cm³ was used in the calculation.

Table 5-1. Weight Comparison of Optional Array to Baseline

	Baseline (2 Mil Cells, 11.1 %)	Optional (6 Mil Cells, 13.5%)
Electric	102.6	136.1
Blanket Support and Stowage	133.6	118.4
Concentrators	132.3	125.1
Extension Mast	12.9	12.9
Misc. Hardware	<u>5.0</u>	<u>5.0</u>
Total per Wing	386.4	397.5
Total Array (2 Wings)	772.8 Kg	795.0 Kg

5.4 OPTIONAL SOLAR ARRAY SUMMARY

Table 5-2 lists the major characteristics of the Optional Solar Array design. Except for size and number of cells, the optional design is identical to the baseline design.

Table 5-2. Major Characteristics

<u>Item</u>	<u>Baseline</u>	<u>Optional</u>
No. Cells per Wing	596,960	490,834
Cell Area per Wing	244 m ²	200 m ²
Blanket Area per Wing	318 m ²	261 m ²
Blanket Size per Wing	4.3 x 73.9 m ²	4.3 x 60.7 m ²
Reflector Size (1 Side)	15 x 73.9 m ²	15 x 60.7 m ²
Total Reflector Area (2 Sides)	2217 m ²	1821 m ²
Power, 1 AU, No Concentration	60 kW	60 kW
Cell Size	2 cm x 2 cm x 0.002 in	2 cm x 2 cm x 0.006 in
Cell Efficiency	11.1 %	13.5 %
Total Weight	773 kG	795 kG

SECTION 6

RECOMMENDATIONS

Great progress has been made in less than six months in the development of designs, selection of materials and refinement of manufacturing processes for the fabrication of ultralightweight solar modules using the recently available 2-mil silicon solar cells. An exciting conceptual design for a variable-concentration concentrator solar array has been identified that meets or exceeds the performance and mass requirements placed on it by the Halley's Comet Ion Drive.

Further design analysis and proof-of-concept experiments should be pursued without delay to enhance the technology readiness status already established. Some pertinent topics for additional investigation are:

1. Long duration (greater than 1000 hr) 1 EUVS exposure on RTV silicone and a modified polyimide-siloxane-co-polymer.
2. Design refinement and thermal test of the flexible interconnect to reduce the interconnect mass.
3. Module fabrication and test using $2 \times 4 \text{ cm}^2$ and $4 \times 4 \text{ cm}^2$ 2-mil solar cells to reduce inter-connect mass and increase module area efficiency.
4. Design of production tooling to accommodate the fabrication and in-process testing of 41 circuit modules (1148 cells/module).
5. Investigation of material properties; such as, pinholes in the cover material using scanning electron microscopy and ultrasonic profiling of solar cells to uncover incipient cell fractures.
6. Experimentally determine solar flux distribution across the exit plane of the compound parabolic concentrator as a function of concentration ratio and sun angle.
7. Obtain cell output data as a function of solar illuminance and cell temperature over the range of values expected for the Halley's Comet Mission.
8. Experimentally determine the optimum method for stowage of large area thin films, as would be found in the solar array concentrator, in the smallest possible volume.

9. Design and test the appropriate sequencing mechanism to be used in concentrator development.
10. Design and test a suitable scale model of the array and concentrator stowage and deployment sequence.
11. Perform the necessary stress and dynamics analysis for the deployment and erection system to arrive at the minimum mass system.



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Enclosed for your systems input and listing in the unlimited unclassified category of STAR, are two copies of the following subcontractor reports:

953984	The Boeing Company - June 1977.
954290	Solarex Corporation - Seventh Quarterly Report, June, 1977.
954328	Battelle - Final Report, February 1, 1977.
954339	Battelle - Seventh Quarterly Report, July 20, 1977.
954344	University of South Carolina - Sixth Quarterly Report, June 27, 1977.
954356	Honeywell Corporation - Sixth Quarterly Report, June 30, 1977.
954373	Crystal Systems Seventh Quarterly Progress Report, July 1, 1977.
954374	Varian Associates - Fifth Quarterly Report, July 7, 1977.
954376	Motorola Incorporated - Fifth Quarterly Technical Report, June 1977.
954393 ✓	General Electric - Assessment Report, July 8, 1977.
954405	Texas Instruments - Annual Report, March, 1977.
954458	Rockwell International - Fifth Quarterly Progress Report, July 1, 1977.

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954521 Simulation Physics - Fourth Quarterly Progress
Report, May, 1977.

954588 Motorola Incorporated - Final Report, April, 1977.

954600 Spectrolab Incorporated - Tenth Monthly Report,
July 15, 1977.

954654 Westinghouse - First Quarterly Report.

954669 Systematic General Corp. - Final Technical
Report, May, 1977.

Very truly yours,


Joseph A. Wynecoop, Manager
Information Support Section
Technical Information and
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